TRANSPORTATION LINEAR REFERENCING TOOLBOXES:
A 'REFLECTIVE PRACTITIONER’S' DESIGN APPROACH

By:

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Abstract

Seventy percent of the data of a typical transportation agency (e.g., bridges, accidents, etc.) has location as a primary reference. A Linear Referencing System (LRS) is the main way of identifying the location of this data and providing a storage key for it in a database. LRS is based on a one-dimensional offset on a predefined network. In theory, it is one of the simplest spatial cases. In reality, it can be spatially and analytically quite complex.

LRS to quite recent date has been little formally researched. That research which has occurred has been the construction of large and comprehensive conceptual data models. This thesis is not primarily aimed at new “tool building research”. The existing models have been based to only a limited extent on a fuller analysis of the nature of transportation and spatial data; they have not considered relevant field and wider methodological concerns (i.e., they followed a “model-driven” approach). The goal here is to create a more appropriate foundation and base from which LRS tools may be most appropriately built (i.e., a “field-driven” approach).

A “practitioners perspective” view of LRS was sought. Such a more holistic understanding was sought through the adoption of a “layered methodology” of research that involved gaining the perspectives of a variety of disciplinary viewpoints. This research framework was developed especially for this thesis based on the ideas and work of Schon and Reich. The approach involved in short a desk exercise in fundamental consideration of the nature of LRS, a deeper, cross-field synthesis and literature research, four in-depth state DOT LRS case studies, a panel of transportation field experts, a panel of national data model experts, and a limited object-orientated modeling exercise.

The conclusion reached is that while LRS in the simple case can be modeled in general forms, it is also an “exception-driven” field. Thus, a “toolkit approach” may be more appropriate for LRS. It is inferred that this may hold for other similar application areas in transportation and planning. Further research would further develop the holistic layered methodology adopted here and further define the proposed LRS transportation application toolboxes.
Technical Acknowledgements

LRS is a *practitioner-focused* field. It draws on multiple disciplines and relates to different transportation activities. In writing this thesis, likewise I have tried to draw on a depth of practical field experience, greater than my own.

While drawing on a set of activities conducted in the 1990’s, the bulk of the research here was conducted largely between 1995 and 1999. It followed on efforts to develop a network conflation toolbox that addressed many of similar topics of this thesis. To complete the work here, a much greater understanding of DOT operational activities was required.

I have been truly deeply indebted to a large number of individuals and certain ongoing research efforts. The effort summarized here has thus been very greatly supported and perhaps quite uniquely benefited from a number of individuals working in the field of LRS over the last ten years. Many of these efforts I was able to initiate with the direct help of many of the individuals below; in other cases other groups were extremely kind to let me participate in their efforts. I am also extremely grateful for interactions with practitioners in a number of parallel fields to LRS.

This work has also reflected continuing part-time dialog and drawing from a set of formal and informal research activities. All of these in various ways have been of very strong import to this work.

I identify here perhaps the ten most significant supporting contributors and efforts to this thesis below:

1) *Thesis advisor:* Mostly, I wish to thank Professor Joe Ferreira, Professor of Urban Planning and Operations Research, and founder of the Computer Resource Lab at MIT. As my professor from 1986 to 2000, he has shown, to say the least, in extreme, much patience. As my thesis advisor, he has supported my interest in the field of GIS and transportation for well over a decade, including with a one-week workshop on Geographical Information Systems for Transportation (GIS-T) and models for transportation planning that were taught together at MIT in 1990. This was a national first. Technically and strategically the field owes much to his many contributions, including his identification of the now fundamental field concepts of “anchor point” and “anchor section” at the 1994 NHCRP 20-27(2) sponsored workshop on LRS in Milwaukee.

2) *Thesis Committee:* Dr. Qing Shen and Dr. Mike Shiffer, faculty of the MIT Department of Urban Studies Computer Resource Lab (CRL), and as thesis committee members, provided important critique and additional energy to me, particularly in the final stages of thesis completion. Their insights on spatial data analysis and the transportation field as a whole were key to many of the insights in this research. Other faculty whose input was important in developing my thinking have been Professor Ralph Gakenheimer (at MIT) and Professor David Bernstein (formerly of MIT, Princeton University and now of James Madison University).
3) **USDOT, National Highway Institute and the Federal Highway Administration (FHWA).** They supported a number of the continuing activities described herein between 1990 and 1999. A number of individuals in US DOT (and the activity of LRS) are owed special thanks. I name three. Particular and special thanks are due firstly to Roger Petzold, FHWA GIS Coordinator, Office of Environment and Planning who exemplifies all that is best in a public servant and to whom the whole GIS-T field owes a large debt for his efforts; secondly, Vinnie Nowakowski (sadly deceased, and much missed) of the former FHWA Office of Technology Applications (OTA), who led many of the technology transfer activities drawn on here; and thirdly Bill Baker, former Head of OTA and who authored the first and only prior generic work on LRS in 1974. As part of their technology demonstration and transfer activities, the FHWA supported a number of projects in this arena. These in part developed the research interests here (and it’s practical application) over a number of years and divergent activities. Projects included developing procedures for reporting HPMS (Highway Performance management System) data through LRS and the development of GIS base for the NHPN (National Highway Planning Network). The technology transfer activities included the following workshops and demonstrations supplied to US and some foreign transportation agencies for which I was fortunate to be selected for Principal Investigator and Principal Instructor:

a. **Geographic Information Systems for Transportation (GIS-T).** Forty 3-day workshops on from 1991 to 1996

b. **GIS and Videologging** (Demonstration Project 85). Sixty 2-day “hands-on” workshops for, from 1992 to 1996. This included taking a highway data collection van to transportation agencies. (The use of such technology is one of reasons for renewed practical interest in LRS).

c. **Integrating Transportation Information Systems (ITIS).** Twenty 3-day workshops on from 1996 to 1999, supplied to DOT Executives, Managers and Practitioners respectively in short, medium-length, and 2 to 3-day versions.

This later workshop presents the broad, enterprise-wide role of information technology in transportation agencies, and acted as a particular backbone for many of the research activities here, including into LRS. These workshops provided a solid base in GIS-T and LRS field issues. The four LRS case studies described were undertaken in part to help support these workshops.

4) **The National Highway Cooperative Research Program (NHCRP).** Under Ken O’Peila (until April 1999) they funded the NHCRP 20-27(1), 20-27(2), and 20-27(3) research projects. Workshops conducted under the auspices for this program greatly contributed to activities here. The results of some of this research are recorded in NHCRP Digest Number 221, March 1998. Professors Al Vonderohe and Teresa Adams of the University of Wisconsin principally conducted these research activities. I have greatly enjoyed a collegial interaction with these individuals over the last decade. David Fletcher has acted as Chairman of the NHCRP Review Panel of these research activities.
5) The USDOT Bureau of Transportation Statistics (BTS). They contributed to support of one of the expert panel workshops described herein. Bruce Spear organized a contribution to the travel expenses for the participants at the EP workshop that was held in March 1999 to compare and contrast the different transportation road data models. This was formally presented at the AASHTO GIS-T Symposium in April 1999.

6) Case Study State Departments of Transportation (DOTs). Four LRS Case Study DOTs are described therein. These four case studies provide the working focus research material that is used as a key to much of the analysis that is conducted. Thus, the participation of the four DOTs was a focal point of the research. In particular, appreciation goes to: Randolph C. Rowell, Idaho Transportation Department; Lee Ann Kell, Karen Lister, and Charles Coldwell (consultant), Missouri Department of Transportation; Frank M. DeSendi, Pennsylvania Department of Transportation; Ron Cihon, Washington State Department of Transportation. In addition, many other individuals generously provided their expertise and experience through interviews and phone conversations.

7) Other Transportation Agencies: Interaction with other US state and Canadian provincial DOTs was highly useful. In particular, activities held at Iowa DOT and Nova Scotia DOT were useful in providing additional information on topics that were considered in the case studies. These agencies allowed a refinement of the ideas described herein by the provision of workshops on the ideas herein.

8) Field Practitioners: Individual field transportation practitioners by their personal interaction have been of much help and stimulation. David Fletcher of GeoParadigm, Ed Granzow Of Iguana, Inc., Al Butler of Hamilton County, N.C., and David Loukes of GeoPlan, Canada, and Jim Dickerson on GPS, in particular, made a number of important interactions and contributions related to field work.

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10) Fellow MIT GIS Doctoral candidates: My fellow MIT Computer Resource Lab (CRL) PhD students in the areas of transportation and GIS greatly aided my education. They include Aurelio Menendez, Steven Ervin, Kamal Azar, Bijan Azad, and John Evans. I particularly benefited from the interactions with John and Bijan on methodological considerations.
If allowed to graduate, I will be the last of this particular special, “spatial bunch”.

The nature of this field required and benefited from a wide range of contributions. The technical acknowledgement list above may be wider than presented for some research. However, it reflects the nature of the wider contributions sought and gained in practitioner-based research. I thank many more who are not explicitly named here, but with whom I have enjoyed and benefited from the interaction.

All the technical mistakes and misrepresentations are fully my own responsibility.
In Memory:

Don Schon, MIT (~-1997), for cognizing the role and importance of educating, "The Reflective Practitioner".

Vinnie Nowakowski, FHWA (~-1998), for providing the opportunity and his time to travel with me to 32 state DOT's and other transportation agencies, reviewing the role of spatial information technology in the field.
Personal Acknowledgements

These personal acknowledgements are shorter than the Technical, but are focused and still more heart-felt.

I would like to enormously and sincerely thank my kind wife, Vicki Lewis. She is also a Geographer, and, more so, wife-extraordinaire. Little did she know what she let herself in for when we met one fine day when I was looking for some transportation network spatial data. One place leads to another.

For this network-focused activity, she has had to assume too far a heavy percentage of the burden (and the joys) of parenthood. This was also while preparing for and executing the US Department of Commerce National Decennial Census (including the street network files) for the Philadelphia region, with management of at times 55 very interesting people, on three shifts.

Our children Aaron and Leah have had to do without an operational dad for rather too long periods. While in many of the research activities described here over the last few years and recent pushes on thesis writing, they have shown, to say the least, exceptional forbearance at my participation. They have not seen their Dad enough (“can I now play computer games again?”). However, we think we already have kids who are both “special cases” and spatial (also, subjects of this thesis).

My mother 17 years ago saw me off to the states, “for a year or two, to do a thesis”. Here it is. My father I will hold responsible for giving me an interest in the nature of transportation-related things since I was age seven. I owe my parents much for their forbearance in my study of matters spatial and transportation over all the years.

Thank you also to my father-in-law for the concluding cartoon. Another graphical dexter.

My hope is that herein may be the basis of a small contribution to a new line of thinking about the relatively ignored science of transportation networks in the context of their nature and form and the description of the events that occur on them. I certainly hope to spend some more time actually traveling on them now with my special spatial family.
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# Abbreviations

A list of terms used in this thesis. A Glossary of terms is provided in Appendix A.

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<td>AADT</td>
<td>Average Annual Daily Traffic</td>
</tr>
<tr>
<td>APTS</td>
<td>Automated Public Transit System</td>
</tr>
<tr>
<td>ATIS</td>
<td>Advanced (or Automated) Traveler Information System</td>
</tr>
<tr>
<td>ATMS</td>
<td>Advanced Transportation Management System</td>
</tr>
<tr>
<td>AVCS</td>
<td>Advanced (or, Automated) Vehicle Control System</td>
</tr>
<tr>
<td>BTS</td>
<td>Bureau of Transportation Statistics (USDOT)</td>
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<tr>
<td>CORBA</td>
<td>Common Object Request Broker Architecture</td>
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<tr>
<td>COTS</td>
<td>Cost-effective Off-the-shelf Software</td>
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<tr>
<td>CSF</td>
<td>Critical Success Factor</td>
</tr>
<tr>
<td>CVOS</td>
<td>Commercial Vehicle Operations Systems</td>
</tr>
<tr>
<td>DGPS</td>
<td>Differential Global Positioning System</td>
</tr>
<tr>
<td>DEM</td>
<td>Digital elevation model</td>
</tr>
<tr>
<td>DLG</td>
<td>Digital line graph</td>
</tr>
<tr>
<td>DMI</td>
<td>Distance Measuring Instrument</td>
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<td>DOD</td>
<td>Department of Defense</td>
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<tr>
<td>DOT</td>
<td>Department of Transportation</td>
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<tr>
<td>EDAM</td>
<td>Engineering Design and Manufacturing</td>
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<tr>
<td>EP</td>
<td>Expert panel</td>
</tr>
<tr>
<td>ER</td>
<td>Entity Relationship (diagramming form)</td>
</tr>
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<td>FHWA</td>
<td>Federal Highway Administration</td>
</tr>
<tr>
<td>FGDC</td>
<td>Federal Geographic Data Committee</td>
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<tr>
<td>GDF</td>
<td>Graphic Data Format (of the International Standards Organization)</td>
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<td>GIS</td>
<td>Geographical Information System</td>
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<td>GIS-T</td>
<td>GIS for Transportation (sometimes referred to as TGIS)</td>
</tr>
<tr>
<td>GPS</td>
<td>Global Positioning System</td>
</tr>
<tr>
<td>HOV</td>
<td>High Occupancy Vehicle, as in HOV lane</td>
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<td>HRR</td>
<td>Highway Research Record</td>
</tr>
<tr>
<td>ID</td>
<td>Identifier</td>
</tr>
<tr>
<td>ISO</td>
<td>International standards organization</td>
</tr>
<tr>
<td>ITD</td>
<td>Idaho Transportation Department</td>
</tr>
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<td>ITIS</td>
<td>Integrating Transportation Information System</td>
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<tr>
<td>ITS</td>
<td>Intelligent Transportation System</td>
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<tr>
<td>IVHS</td>
<td>Intelligent Vehicle Highway System</td>
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<td>MoDOT</td>
<td>Missouri Department of Transportation</td>
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<td>MPO</td>
<td>Metropolitan Planning Organization</td>
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<td>NCGIA</td>
<td>National Center for Geographic Information and Analysis</td>
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<td>NCHRP</td>
<td>National Cooperative Highway Research Program</td>
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<td>NSDI</td>
<td>National Spatial Data Infrastructure</td>
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<td>OO</td>
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<td>Open GIS Consortium</td>
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<td>OMG</td>
<td>Object Management Group</td>
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<td>PIS</td>
<td>Planning Information System</td>
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<td>PennDOT</td>
<td>Pennsylvania Department of Transportation</td>
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<td>POTS</td>
<td>Proven off-the-shelf software</td>
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<tr>
<td>RDBMS</td>
<td>Relational Database Management System</td>
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<tr>
<td>RP</td>
<td>Reference Post</td>
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<tr>
<td>S/A</td>
<td>Selective Availability (GPS term)</td>
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<td>SDTS</td>
<td>Spatial Data Transfer Standard</td>
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<td>SLD</td>
<td>Straight line diagram</td>
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<td>TGIS</td>
<td>Time-enabled GIS</td>
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<td>TIGER</td>
<td>Topologically Integrated Graphically Encoded Record (US Census street file)</td>
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<td>TIS</td>
<td>Transportation Information System</td>
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<td>Transportation Network Profile (SDTS)</td>
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<tr>
<td>UML</td>
<td>Unified Modeling Language</td>
</tr>
<tr>
<td>USDOT</td>
<td>United States Department of Transportation</td>
</tr>
<tr>
<td>UTM</td>
<td>Universal Transverse Mercator (Coordinate systems)</td>
</tr>
<tr>
<td>USGS</td>
<td>United States Geological Survey</td>
</tr>
<tr>
<td>WADGPS</td>
<td>Wide Area Digital Global Positioning System</td>
</tr>
<tr>
<td>WGS84</td>
<td>World Geodetic System 84</td>
</tr>
<tr>
<td>WSDOT</td>
<td>Washington State Department of Transportation</td>
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</tbody>
</table>
1 Introduction

"We are not lost. We are locationally challenged".
John M. Ford.

1.1 General Introduction

1.1.1 The Research Gap

Transportation is an art and a science that grows out of the fundamental human need to conquer space. Transportation is essentially about moving goods or people from one location to another location. It is thus, first, may be considered as a “locational science”. Transportation practitioners thus have a prime concern with “traversals” (or “routes”) from location A to location B (or, their collection in “networks”). Transportation (or transportation network science) should thus includes the management and description of transportation traversals, and the recording and analysis of events and activities that occur on them. Ask anyone who has used a cellular phone in a car, train or on a freight shipping trip – when calling home, did they report absolute, or, relative (traversal-based) location? One is more generally more likely to state, “I am ten miles past Baltimore”, or, ‘I am near MacDonald’s” than I am at latitude x and longitude y. Even when seemingly absolute location is reported, (e.g., “The train is at Baltimore Penn Station”), the context is often linearly driven. Transportation is thus in large part in the field a relative linear or (network) context-driven activity and science.

The previous statements are elemental to transportation. However, this thesis will argue that these basic observations are have not been fully reflected in the emphasis by which transportation has been understood and studied, especially by disciplines which are more “absolute” in their consideration and operation. (This is reflected even in current transportation university programs and research). This thesis is an attempt to fill this fundamental gap in the analysis of transportation to date. In particular, it seeks to make a potential contribution in concepts of transportation network data management.

1.1.2 Research Context

From the earliest days of mankind and foot-driven transportation, to modern man with cellular phone, the need to define and cross-reference at least transportation relative location has been with us. Primeval man marked pathways. Spatial analysis grew more complete and more closely mapped physical reality over the centuries. Geographic analysis using computers to facilitate the process began about 30 years ago.

Today some fundamental research in the general spatial analysis field exists. It has some partial coherence through some national coordinating efforts, such the Federal Geographic Coordinating Committee (Federal Register, 1994) and the National Center for Geographic Information and Analysis (NCGIA) (NCGIA, 1999). However, in a wider analysis, given the increasing scale and importance and application of spatial activities and analysis, the theoretical development of the
field has relatively suffered from some lack of wider continuing support, focus and cross-disciplinary working. As a science the field has grown, though mainly to date through commercial application (Zeitler, 1999).

There have been some significant advances, in some important areas of spatial analysis, in the last 10 to 15 years. For example, approaches have been developed to readily convert between map projection systems. Methods have been developed to deal with more complex spatial recognition issues, such as building spatially logically organized (i.e., topological) data structures from “map spaghetti” (i.e., uncoordinated linework), including for example methods and algorithms to topologically recognize various versions of the “island within island problem”. (Samet, 1990, Zeitler, 1999). However, the art and a science of many areas of spatial analysis – the synthesis of how we really understand, consider and map space – is still at a basic level of development in many areas. Most attention and developments to date have focused on the processing of polygons. It is thus very appropriate to visit some of the basic foundational bases on which locational analysis and GIS stands.

Linear referencing is an example of an area that would appear to critically benefit from such examination. Linear Referencing Systems (LRS) are concerned with a locational reference in one-dimensional space – that is, an offset from some predefined position on a network. LRS indicate location on a line that traces out the path of travel (a traversal). This path can be transcribed by many types of line. However, typically a single line is used to represent dual directions.

The formal literature and research on LRS was quite small (even nearly non-existent) until the mid 1990’s. Since then it has been a focus of some diverse field attention and practitioner review. LRS has had less formal or comprehensive research efforts and the work that has been undertaken has not been coordinated across the transportation field as a whole. In fact, the field benefited (and has perhaps at times suffered) from a number of recent focused and separate research initiatives. One of the main fundamental and necessary tasks of the research here has been to attempt to draw together some of these efforts.

By understanding the simplest theoretical case, sometimes we better understand the more complex case. By focusing on the apparently more simple case, we may better develop standpoints and tools to later analyze the situations that are really complex. However, in some instances, research shows that the apparently simple case is indeed quite complex. The technical area of one-dimension referencing is arguably the simplest spatial location referencing case. It is the one chosen for this thesis. Certainly, the maxims of simplicity and complexity combined exist here.

The topic of “how we actually think about and achieve one-dimensional referencing” can be argued to be simpler than the analysis of a zero-dimensional case, points. This is because practically we will always analyze points in some context (that is, area or space), which is at least two-dimensional (D). The LRS case in theory at least pre-assumes placement with (or at least association with) a network. Networks are associated with many fields (e.g., telecommunications, computers, utilities and social interaction research, etc.). Here, the domain of transportation is chosen for focus. A “field practitioner’s viewpoint” is the practical concern of this thesis. One description of this analysis point is: “The model is only useful if it fits my business professional practice and helps me do it better”.

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1 NCGIA funding Is believed to have now ended, though some social science extensions have been granted

30
Linear referencing is:

1. In operational terms, a "messy problem", and,
2. In research terms, "a new" focus area, at least for more formal research.

This first chapter briefly, introduces the research topic and focus of the thesis -- "how do we best set up schema for where we are in one-dimensional space?" It reviews some of the issues associated with this field. The chapter concludes with a summary of the goals of the thesis and an overview of thesis organization.

1.2 LRS: A Spatial Context

This section gives a brief review of the historical context for spatial and linear transportation measurement.

1.2.1 Personal Location: Where am I?

Where am I? Where am I in context of my last or next expected reference point? Location in space is a challenge that is addressed by each one of us throughout the day. It is a topic that can also be more formally addressed from many academic, professional, operational and working disciplines and perspectives.

Babies by one year have to find out about the size and shape and "moveableness" of everything in their world." (Spock and Rothenburg, 1992). We are always "somewhere in space". "Place" presents itself to us as a condition of human experience. "As agents in the world we are always "in place", much as we are always in culture" (Entrikin, 1991).

Knowing where one is located is a vital question throughout the day, to any being. It is not thus surprising that the evaluation of that bare fact has much Context associated with it for the traveler. "Context" is critical (in fact absolutely necessary) to one's estimation of where one is in both relative and absolute terms. Context or standpoint (and one's subsequent language) can be formed and defined by training and discipline and current physical and social circumstances and needs. Analyses needs to thence be made of how one views where one is in space. Physically, I may have a GPS receiver and know my exact GPS latitude and longitude; however, if I cannot see the road over the sand dunes (or, do not have an accurate map to match with the coordinates), I may feel totally lost. Or, if I am a Surveyor by discipline, I may feel that all data should be collected and stored by extremely accurate measurements, but I may not know or understand the wider set of "data issues" (e.g., database design, issues of data redundancy, etc.) and "people issues" (e.g., the business process change issues), that may be involved in any fuller analysis.

How do we keep track of where we are in space? Recent research has shown that, 1) not one part of the human brain but several parts help keep track of things in space, and, 2) spatial processing seems to be broken up in a kind of "divide and conquer" method (Richardson, 1998). Neurons encode information about an objects location and retain a short-term memory of it.

Men and women think differently about space. For a traversal or trip, men typically prefer an (abstract) map (2D), women directions or landmarks along a proposed path or route. Gould and White in their book "Mental Maps" trace the way different groups think about or conceive space.
Gould and White, 1974). Child, adult, man, woman, we need societally (from personally through to professionally) accepted methods to both keep track of things in space and pass this positional information onto others. We then further need formalisms to further logically analyze where we are "in place" or "in space".

1.2.2 Societal Spatial Activities and Organization

From the very earliest days of mankind in Mesopotamia society has sought to arrange itself "in space". This was done so that human activities could be engendered and optimized. Chapter 4 verse 17 of the book of Genesis notes that Cain, a son of Adam and Eve, "was then building a city". Thus from the earliest of human days, urban activities were located "in space" in some logical fashion. These activities were so organized after the flood of Noah that in Chapter 11 of Genesis, God, concerned that mankind was making itself haughty and not going to scatter across the world at this time, said:

"If as one people speaking the same language they have begun to do this, then nothing they plan to do will be impossible for them. Come, let us go down and confuse their language so that they will not understand each other". (Genesis, Chapter 11, v5-6).

This urban development continued across the millennia as civilization struck out across the world.

There is in Egypt a small town of Kahun, built nearly five thousand years ago. It was designed to house workers on a nearby pyramid, and since it was presumably therefore planned in a commonplace, we may assume from its regular pattern of blocks intersected by a grid of streets that the Egyptians of the third millennium BC saw nothing novel in wholly artificial urban planning" (Bell, 1972).

The study of the urban and regional form and spatial interaction patterns was for a long period principally the domain of early mapmakers and then geographers. A cadastral map of the city of Babylon was produced in 2200 BC (Tooley, 1987). The Egyptians produced maps of the Nile valley. The Egyptians were amongst the first not only to produce maps of "what was" but also created predictive models of "what would be" (that is, when the Nile would flood certain geographic areas). The Greeks through Ptolemy then influenced geographic thinking for 1500 years. Ptolemy's Geographia assimilated much of the geographic information and knowledge then available (in the library of Alexandria) and introduced the concepts of latitude and longitude to reference it.

The development of large cities (Rome reached perhaps 750,000) created a greater need to manage urban space. The Romans also brought urbanization and planning to their colonies — 170 cities in Gaul and 40 in Britain. It was said that the Roman military "carried urban plans in their military backpacks".

The organization of society led to the search for order or spatial patterns in those activities. Spatial order and pattern can only be readily established within a common reference system.

1.2.3 History of Linear Travel Measurement

Linear measures are one of the most basic spatial orders used, probably dating back to time elapsed along established pathways by primeval man. More formal and exact linear
measurement along roads has been discernibly in use for at least two thousand years, dating back with best record to the use of 'mile' stones in Roman times. Roman maps were very linear in their design and orientation. “Roman road maps distorted sea and land masses in order to fit the imperial road system into a confined pace” (Tooley and Bricker, 1976, p.22). They in effect acted as “linear itineraries”. A Roman centurion standing on Hadrian’s Wall in Scotland knew exactly how many “mile” he was from Rome. A straight highway in Britain was until recently always called “a Roman road” (the Middle Ages mainly leaving roads that followed the “edges” – the field boundaries). The very term “highway” comes from Roman times as the Roman engineers elevated the roadway 2 meters for defensive purposes.

The Romans recognized the wider importance of transportation standards. A Roman mile was 1000 double-paces or 2000 paces, which equates to 1620 yards. Roads were constructed to a common form, size and carrying capacity. “Mile-markers” were set up and maintained by the local jurisdiction. Where three Roman roads met (a “tri via”) signs and news were posted (hence our modern day word, “trivia”). Post houses were located every 10 to 15 miles and inns every 20 to 30 miles. A day’s march was typically 25 miles. With the use of the 55,000-mile Roman road system with an army of 180,000 soldiers, Rome was able to control an empire estimated at its maximum at 55 million people.

Later less organized centuries of people were only able to marvel at the Roman road system, thinking that giants had laid them. Highway marker systems were locally used throughout the centuries, but were not so rigorously or universally applied again until this century. Widespread use of highway markers in the United States in fact began with concrete mileposts installed on the roadways of a few states in the early 1920s. The realignment and abandonment of roads, and construction of new roads, made many of the old mileage signs virtually useless and signs displaying point-to-point distances and route numbers based on the uniform highway numbering system gradually replaced them.

The use of mileposts in the US took on new significance when the Highway Acts of 1956 and 1966. These Acts required their use as a basic element in the planning, construction, and administration of the national highway system, and in the identification of accident locations. This contrasts markedly with their earlier use as a device primarily for the convenience of travelers.

Some states adopted LRS (e.g., Texas) as early as the 1920’s, with the installation of their highway mile-marker systems. However, for some agencies and states, this has been a much more recent innovation (e.g., Nova Scotia, in 1990).

1.2.4 New Topic For Formal Research

In a relatively new research area, and in particular with messy problems, to best analyze a problem, one has to “travel through different frameworks of analysis and understand the vehicles that can transport one”. Thence, by necessity, on a wider basis, this thesis is about how one frames, thinks about and undertakes research of Planning or spatial data or analysis related issues. How best to research LRS became early identified as a research issue itself.

2 The distance between railroad tracks in the United States and elsewhere today derives back to the distance between cartwheels through the middle ages. Carts had to have a common spacing otherwise they would not be in rut. This measurement was adopted back in the days of Roman occupation of Europe. The standard had been set by Caesar as the distance across two Roman warhorses.
The wider field of methodology for how to conduct spatially related research (and also practitioner focused research) is still finding its feet. In gaining the wider goal of LRS research, a humble goal of contributing how to conduct or even better think about spatial research was a necessary by-product— in fact also a first required product.

1.3 Linear Referencing Systems

This section briefly introduces the terms and concepts of LRS.

1.3.1 Basic LRS Key Concepts and Terminology

The language of where I am in space is often ambiguous and confusing. It is partly a function of the English language, which is often flexible but not precise. Different individuals, authors and transportation agencies and groups often use the same term with quite different meanings. For example, the term “route” means different things to a highway maintenance engineer or a bus operator. To the highway engineer, the route is made of fixed number of whole highway “control sections”; to the bus operator, a route may be made up of time variant whole and partial highway sections. At the level of linear referencing data models, in particular, fine distinctions are made as to the meaning of different terms (see for example, Vonderohe et al., 1997; Dueker and Butler, 1997; USGS, 1992).

The set of terminology used to deal with LRS (e.g., route, milepost, etc.) overlaps with but is distinct from that that terminology developed to deal with flows on networks (e.g., “centroid connector”, “traffic zone”, etc), or, graph theory (e.g., “edges”, etc). LRS presumes the existence of a “network” (or, at the least one traversal, or historically hunting path or military way). A network may be simply defined now as a connected collection of “links” (transportation model term) or “arcs” (topological term). The network is typically defined as a set of lines (or, arcs); to date in field use, it is has more typically not been an accurate geometric representation.

All of us daily use many forms of both physical and conceptual networks and the term is intuitive to us. This thesis focuses on transportation networks and thus refers to “linear referencing” in the context of roadways, which includes all traveled roads. Of course, linear referencing is not confined to roadways, and has been applied equally well to railways, rivers, pipelines, electric lines, fault lines and other linear features. Use of the term ‘roadway’ or ‘highway’ in no way diminishes the importance of linear referencing to these other transportation or geographical networks. In fact, many transportation agencies wish to extend their use of linear referencing on roadways to other modes of transportation. However, linear referencing has most prominently been used for ‘roadways’, which is much more convenient than specifying ‘linear feature’.

1.3.2 The LRS Technical Model

The basic LRS elements are basically very simple. There are three basic common main elements:

1. Known point (which assumes that are already defined, a transport system, traversal system, traversal reference point)
2. Direction from a known point
3. Distance from the known point.
The point "event" B is distance x from the base point A. The basic elements of a simple linear referencing system are shown in Figure 1.

**Figure 1 Simple Linear Referencing: Base Point Method**

This model is intuitively very simple. However, the context and implementation are what makes, "matters from here get more complicated". For example, these ten example basic questions indicate how the issues in the field become richer:

1. Who defines the network transport system (and what is their viewpoint)?
2. Who defines "the known points”? Is it the same person/group as 1)?
3. How accurately does "the distance" have to be measured?
4. Who needs "the traversal reference system”? Who defines and maintains it?
5. How technically is the traversal reference system defined? (e.g., is it continuous, etc).
6. Are measurements along the road bi-directional in value?
7. How is the known point defined (e.g., center of intersection, gore point, etc)?
8. Does an incident (such as an accident) happen at “a point”, or, along a distance?
9. Is the distance “flatland” distance, or is it a three-dimensional distance?
10. How exactly are the coordinates of the point calculated?

This thesis will discover many other such questions that will indicate that LRS is not "just an offset problem”.

**1.3.3 Linear Referencing Field Issues**

Linear referencing to work must provide a wider set of methods and procedures for recording and retrieving locations along linear networks. Modern transportation infrastructure is complex, three-dimensional, multimodal and relatively often changing due to realignments and other construction or re-arrangements in the highway layout or operating pattern. A stable linear environment in which to collect, store, and retrieve locations may not exist for more than a year or two. The cost of errors may grow in proportion to inventory complexity. Can I do accident
and safety analysis of Route 30 if what is called “Route 30” has been significantly changed over the last 5 years? In short, it has been said, that with the setup and use of LRS, the “devil is in the details”.

For example, the following practical example cases often present difficulties for managing linear locations:

1. Corrections to traversal (or ‘route’) lengths or measures (no physical change to the network)
2. Realignments (modified network, often affecting ‘downstream’ traversal measures)
3. New and abandoned roadways that may impact portions of traversals and their measures
4. The introduction of a new nodes along a route (that could impact an existing traversal)
5. The definition of traversals for divided highways, ramps and other special types of linear features.

Other field complications exist as well which have not been researched in a more coordinated effort to date. For example:

1. How can locations obtained by different linear referencing methods be translated and integrated?
2. The Global Positioning System (GPS) now enables collection of locations with sub-meter accuracy – how can these best be linked with linear measures?
3. How can linear referencing, which changes over time, be best applied to manage historical data?

A principal objective of this research is to help transportation practitioners develop and manage linear reference systems in today’s complex infrastructure environment. This research presents the experience of the case studies and will provide preliminary recommendations on how to address these and related LRS issues. There are basic LRS issues, such as how to code traversal identifiers or when to use of separate traversals for each travel direction. These issues become more complicated given the variety of even basic road features, some of which are exampled in Table 1, below. This table illustrates some of the transportation data spatial variety that occurs and needs to be encoded. For example, does which way one codes or lay out the traversal round the cul-de-sac or rotary determine where you are in “linear space”?

Field and desk examination of the transportation agency LRS reports listed in Appendix C has indicated that some current key LRS research issues include:

A: Basic or Key Issues:

1. How should each infrastructure type (as shown in Table 1) best be handled?
2. Can current business practice and linear referencing accommodate full and complete descriptions of every possible location?
# Table 1 Real World Highway Features and Networks

<table>
<thead>
<tr>
<th>#</th>
<th>FEATURE</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Travelway</td>
<td>The portion of a roadway for the movement of vehicles, exclusive of shoulders</td>
</tr>
<tr>
<td>2</td>
<td>Divided Highway</td>
<td>A highway with separated roadbeds for traffic in opposing directions</td>
</tr>
<tr>
<td>3</td>
<td>Ramp</td>
<td>A connecting roadway between a freeway or expressway and another highway, road, or roadside area</td>
</tr>
<tr>
<td>4</td>
<td>Frontage Road</td>
<td>A local street or road auxiliary to and located on the side of the arterial highway for service to abutting property and adjacent areas and for control of access</td>
</tr>
<tr>
<td>5</td>
<td>Layered or tiered roadways</td>
<td>Roads not at grade, or with multiple levels, such a dual level bi-directional bridge</td>
</tr>
<tr>
<td>6</td>
<td>One-way pairs (individual lanes, inc HOV)</td>
<td>Divided highway on one direction</td>
</tr>
<tr>
<td>7</td>
<td>Intersection</td>
<td>The general area where two or more roadways join or cross, within which are included roadside facilities for traffic movements in the area</td>
</tr>
<tr>
<td>8</td>
<td>Interchange</td>
<td>A system of interconnecting roadways in conjunction with one or more grade separations providing for the interchange of traffic between two or more roadways on different levels</td>
</tr>
<tr>
<td>8</td>
<td>Rotaries</td>
<td>A traffic circle</td>
</tr>
<tr>
<td>9</td>
<td>Cul-de-sacs</td>
<td>A local street open at only one end only, with special provisions for turning around</td>
</tr>
<tr>
<td>10</td>
<td>Dead end street</td>
<td>A local street open at one end only, without special provisions for turning around</td>
</tr>
</tbody>
</table>
B: Additional research issues include:

3. Determination of optimal traversal/section lengths (e.g., short, county length, state length, etc).
4. Calibration or traversal measures
5. Specification of event locations, and
6. The synchronization process between LRS control and event databases.

This thesis attempts to address these research questions issues in turn in a little depth, utilizing examples taken directly from each of the four transportation agency case studies.

As information systems become more capable, more options are available for maintaining historical information for trend analysis. Linear referencing as typically implemented has a particular limitation in this regard. Information in separate roadway-related databases (e.g., pavement and traffic data) can be integrated based on where things occur on the ground. However, mile-points (or other measures along traversals) are typically updated over time due to re-measurements, realignments or other construction. Therefore, the mile-point of a particular location may change over time. This complicates the integration of separate transportation databases and, in particular, the management of historical data. Issues and techniques of managing historical data are discussed, along with the experience of the case studies.

Bound within these implementation issues are the relevant mandates and business processes of transportation organizations. Methods for managing information about each infrastructure element, including its location, must be well-defined in order to meet program objectives. Many transportation organizations face problems related to new infrastructure types that cannot be defined within existing LRS business practices. This is often a driving force behind the re-engineering of many LRS's. By focusing on LRS "best practices", the main body of this thesis presents both mainstream issues and idiosyncrasies (many of which are in fact relatively still quite common) that transportation agencies have or will encounter during their LRS development.

1.4 Current Spatial Information Management and LRS Usage

This section briefly reviews the challenges and progress that DOTs have made in spatial information management and their use of LRS to date.

1.4.1 Spatial Information Management

In the last decade or so, spatial data has become relatively much cheaper and more readily available. Measured in units such as megabytes, number of files, and available sources, there has been a relative explosion in the relative and absolute volume of agency spatial data. This has resulted form two principal data collection causes.

1: General Improvements: Improvements in spatial data collection technologies, have made them more cost-effective and technically improved (e.g., GPS and DGPS, laser swathe mapping, aerial photogrammetry, etc.).

2: Specific Improvements: These include specific developments geared to DOT's, such as off-the-shelf highway data collection and analysis packages geared to
DOT’s (for example, ARAN and videolog vans, etc). These technical developments are increasingly making large volumes of principally spatially related data available to DOT’s that were not readily available before.

Collection of the data involves one set of issues (involving for example field data collection skills). Management of the (collected) data asset involves another set of issues (involving spatial data management skills). Both have unique foci. Spatial datasets, to gain even a portion of their potential full utility, need to be integrated (both with other new data-sets and existing agency legacy data-sets) and also corporately managed and maintained. A strategy needs to be in place to organize the increasing volumes of spatial data.

Thus, the significant increase in spatial data has made necessary the adoption of methods and tools for managing spatial data. The common adoption, set-up, and use of relatively off-the-shelf mature spatial data processing technologies, including, standard relational and database technologies, Geographic Information Systems (GIS), and GIS for Transportation (GIS-T), have further necessitated the adoption of a single “location reference method” for transportation data. Computerized cross data-set analysis methods work best on common indices.

Many DOT business requirements and applications benefit from the integration of data from different DOT work-groups, sections and activities. For example, safety analysis critically typically requires bringing data together or integration of data from different sources. As location is the key for much of this data, it is necessary to form a common “locational referencing system”. For many state DOT’s, LRS provide the framework for integrating network data from many core business activities (e.g., pavement management, bridge management, maintenance scheduling, safety analysis, etc).

LRS, seen as enterprise integration tools, require a common agency-wide technical vision and institutional agreements, to best set-up and implement. Once set-up, they are then relatively expensive to change. One reason for this is that wider DOT agency business practices evolve around them. Therefore, typically, a LRS framework may itself be regarded as a “foundational business (information) system” (or, a key common component of agency business systems). As an agency-level, foundational, system, it may be considered for change with other such foundational DOT systems, typically only say every 20 to 30 years.

From evidence obtained from workshop interaction undertaken for this thesis, many LRSs developed over recent decades are not sufficiently robust to handle the information needs of today’s transportation agencies. Specifically, linear referencing provides a foundation for geographic information systems (GIS) for transportation (GIS-T), integrating transportation information systems (ITIS), and intelligent transportation systems (ITS). How these concepts are brought into use rests squarely on the shoulders of established LRS’s and their robustness to accommodate fundamental changes in daily business practice.

Over the past six years in particular, there has been considerable but uncoordinated research into LRS models as a means for integrating transportation-related data, as well as its applicability to complex initiatives like ITS. In part in response to such initiatives, as well as increased demands to better manage the data asset, many transportation agencies are attempting to revise their linear and location referencing systems to support these emerging business needs. Learning lessons on how they have responded is a challenge that this thesis sets itself to.
1.4.2 LRS Field Use

This sub-section briefly reviews modern-day LRS field use, with a focus on North America.

In the US, many DOT’s have had LRS in use for sometime, in some as long as 70 years. Local agencies are only just beginning to adopt LRS. In 2000, the AASHTO GIS-T Symposium, the practitioner conference where LRS issues are most reviewed, met for its twelfth year. (AASHTO, 2000). At this event, 40 out of 50 states have reported some measure of development in the GIS-T area. Many of these states included note of some current review or recent update development of their use of their LRS systems.

A number of US state DOT’s in the 1990’s (e.g., Iowa, Texas, Delaware, Minnesota, Florida, etc.) have recently reported formally reviewing their use of LRS. In a number of these cases, efforts to put in place new LRS’s were initiated. Not all of these efforts were deemed by internal or external sources “to be wholly successful”. Many agencies are currently reviewing their systems in place.

A review of these efforts from both published LRS reports and on-site examination has indicates that in short:

1. Complexity: LRS looked simple, but was indeed more complex in the implementation (again, “the devil was in the detail of LRS”). For example, the design of the Maine DOT Data Warehousing effort has been fundamentally tied to the organization of legacy highway data sets. At the same time, new automated data collection vehicles, generating linearly referenced data in volumes not experienced before, have required the setup of LRS that can be matched with common vehicle data collection traversal paths (for example, the Connecticut DOT videolog program, etc). The needs and use for new traversals have not matched the old.

2. Success Rate: “Not so successful” LRS implementations have been occurring. Several DOTs have had to “revisit their recently revisited” LRS efforts. Agencies are not keen to advertise some of the engineering and re-engineering that has gone on in this and other areas. A second LRS design effort has gone into place for example in recent years in Iowa and Texas DOTs. Reasons for LRS relative failure are hard to fully discern, as departments are not keen for failure to be discerned and analyzed. The complexity of LRS may be one factor.

Examples of particular LRS implementation difficulties experienced include:

a) Geometric update: The alignment of the road is changed. How are the database distance elements changed?

b) Temporal update: There is a wish to carry out analysis of the roadway (which may or not have a changed configuration) over a historic time period. Which set of highway elements is included?
c) Differences in user interface: Different groups in a DOT may have grown used to looking at linearly referenced data in different manners and may wish to continue doing this. Accidents may be referenced by distance from an intersection or a landmark, while an ARAN van may log data by a route mile-point system.

d) Network Representational Issues: A highway may be represented as a simple single linear feature, divided highways may be allowed, display of ramps, etc. Different groups within a DOT may use these different representations.

e) Network Conflation: The integration of data across different spatial networks (in theory, more difficult) and different LRS’s (in theory, easier) are in reality for practical reasons quite difficult.

3. **COTS/POTS:** The set-up of LRS should be practically tied to the availability of commercial off-the-shelf software (COTS) or POTS (proven off-the-shelf) technology to support it. For example, in moving towards an improved LRS framework, Texas DOT has adopted an intermediate format until vendors fully supported improved LRS models.

4. **Wider Institutional Integration And Data Sharing:** Considerations of cost efficiencies, agency-level data accessibility and conducting analysis on common data sets have led many DOTs to increase their goals for data sharing. In this environment, fuller review and recommendation on optimal design of state-level LRS has been seen to be typically a matter ultimately beyond one agency alone. Those concerned may include local agencies, utility and delivery companies, federal agencies, GIS vendors, database vendors, and possible a variety of field practice and practitioner input, etc.

As indicated, as a result of these and other such considerations, there has thus been a renewed interest in LRS. A small number of nationally sponsored and individually undertaken research initiatives have been put in place. This was also in large part stimulated by the advent of the new data collection and data processing technologies (as described in Chapter 3). These again also made appropriate, if not necessitated, an updated review of better practices for the LRS’s that transportation agencies employed (or, planned to employ). However, in addition, clearly, previously established LRS did not meet the data processing and analysis needs of the 1990’s and the new millennium. Thus, many North American transportation agencies have also had a relatively strong renewed focus on LRS.

Linear referencing, the means of specifying locations along linear features, is a foundational key or index for most transportation data management practice. The basic concepts of linear referencing remain unchanged since the seminal federal guide to linear referencing was published (Baker and Blessing, 1974). This work has remained almost to date as the only wider guide to the field. However, recent technology has pushed horizons to a point that a comprehensive wider review of LRS is required. New methods for data collection, such as GPS, video-logging and
remote imagery, call for more comprehensive methods for managing and integrating the greatly increased volumes of location-specific data.

Practitioners of linear referencing include system designers, technicians and managers involved in activities such as:

1. Evaluating existing linear (and location) referencing systems
2. Extending a linear referencing system to incorporate new features (local roads, ramps, etc.)
3. Developing new linear referencing systems
4. Implementing an existing linear referencing system using GIS
5. Designing database structures for linearly referenced data
6. Integrating data using different linear referencing system
7. Integrating linearly referenced data with other location referencing methods (e.g., GPS).

It will be explored in this thesis that LRS can be seen as much (if not more) as a data management tool than as a measurement device.

1.5 Objectives of the Thesis

This section reviews both the focused LRS research goals of the thesis. It also summarizes how these relate to wider research goals in the field. Goals reviewed here include:

1. Technical Goals
2. Planning Research Goals.

1.5.1 LRS Technical Goals

A technical goal of the thesis is to provide a solid research base for practitioners that are contemplating the adoption, integration, or major modification of their linear (or location) referencing systems. New technologies abound, the cost of data collection has dropped significantly and field attainable accuracy exceeds that of existing base maps by orders of magnitude. The question faced by the transportation information community (which is in fact several information "sub-communities") is, how to build a location referencing system that can endure the fast pace of technological change and thus assure that large investments in data will meet future needs. Many national research projects are underway, and the central thread through every initiative and case study is well-informed planning and full utilization of the hard-earned experience of other transportation agencies.

The tools to collect data about and analyze “where I am in place” have greatly improved in recent years. This thesis as a whole in summary makes the argument that while locational tools have improved, the endemic and inherent complexity of defining “where I am in space” still leads to many difficulties in creating simple, robust and useable geographic or “space handling” models.

This argument is pursued entirely in this work by examining in detail the simplest locational case. This is defining location in a one-dimensional form when position is expressed on a pre-defined network. In the one-dimensional locational case, location is expressed as some distance x from a
given, known, point. The Roman Centurion knew how many “miles” he was from Rome on Roman highways. The soldier was in effect using a LRS.

It is argued here that the one-dimensional referencing case is the simplest case, since only one dimension is involved (x). Defining a point requires the expression of at least two if not three dimensions (x, y, z). However, it may be argued that handling a point is simpler as it’s coordinates (coordinate pair) can be expressed more freely with respect to some standard coordinate system (such as a state plane coordinate system). It may be argued that such universally accepted “ordinate” systems do not exist for the one-dimensional case, and that is at the crux of the problem before us.

Many disciplines utilize space or location as a vital part of their endeavor. Consideration of LRS to date has not been an area of focused academic focus inquiry.

As an end objective of this research, it is hoped that as one benefit from this LRS field practitioners will gain the relevant technical guidance they need to accomplish their work in a rapidly changing technological environment. In addition, it is hoped that the thesis will provide a broader view of issues related to management of information across the transportation organization. The development of ITIS is based on LRS.

1.5.2 Planning Research Goals

To build a house you need a hammer. If you do not have one, one must be fashioned. “How to research or frame the LRS issue” was a research issue.

This thesis aims, through focus on a specific topic, and contemplation on the results of that endeavor, to offer some insight into a higher class of problem – how to conduct research in this type of domain. These concerns include:

1. **Information System Research:** The classes of issues one generally faces in building and researching:
   a. Planning information systems (PIS).
   b. GIS and spatial analysis.

2. **Planning Research:** The still wider set of issues in conducting Planning and Planning-related analysis. That is, placing “Planning” – and doing “Planning”, as a whole, in some wider contextual framework.

The aim here was thus not to be one more attempt at “a unified model for LRS”. There have been four or five attempts at that already. There has been somewhat poor historical attempt at coordination, leaving an outstanding research issue of integrating the prior research that had been undertaken. Critique to the models produced to date is undertaken drawing on the results of the “practitioners approach” take herein. In model terms, the primary purpose of this thesis is to provide the basis on which appropriate forms of models may be further subsequently selected and built – presuming, that indeed “one model” is appropriate.

As a relatively new area of focused research, an attempt has been to lay out a methodology that may potentially be duplicated, repeated and improved upon in subsequent work. It is hoped that
the delineation of the framework described here – and its further development – may be a minor contribution to the field as such seems to have not been well laid out to date.

Some conclusions on these topics are drawn in the final chapter.

1.5.3 Fuller Research Goals Enumerated

In summary, the most important goals of this thesis are:

1. **Methodology**: To research appropriate and draw wide conclusions methodologies for spatial information systems analysis for GIS and PIS. From the literature search, it seems to date that such has been given limited attention to date. Basic inference and some exploratory work is done for an improved methodology to work forward is provided, utilizing what has been learnt in this research.

2. **Comprehensive Field Exposition**: The current state of linear referencing and experience gained to date has not been to date compiled, organized or analyzed in a more comprehensive format or framework. This is primal wider goal of the research here. That is, to lay out a basic but more comprehensive exposition of LRS. Arguably this has not occurred in more comprehensive form since the 1974 FHWA report on LRS (Baker, 1974). While there has been much accumulation of individual papers on LRS, often dealing with individual agency systems, there has been little comparative review and analysis on any systematized basis. The attempt of the research here is to make a contribution in this area.

3. **Analysis**: To provide some critique and analysis of this freshly accumulated body of knowledge.

4. **Spatial Data Issues**: The issue of LRS, which has much practical importance to the transportation and departments of transportation, state, regional and local, touches hard on a much wider research issue. Thus the research has the goal to more fully understand (by classification and analysis) why in this field, even the most simple, one-dimensional locational case, represents significant practical difficulties. As a full analysis of even the one-dimensional case has not been prepared before, this thesis focuses much of its effort in achieving this goal.

5. **Spatial “exception handling”**: To propose, based on this understanding, at least potentially improved ways forward for LRS, based on “exception handling”.

6. **Wider Field Inference**: To draw wider inference on Planning Information Systems (PIS) and spatial exception handling.

7. **LRS Framework**: Indicate a preferred framework for the development of LRS

8. **Further research**: Indicate directions for further research.

This thesis thus aims above all to be a more comprehensive, systematic analysis of the wider field of linear referencing. In the general background described, common to all North American DOT’s, it is therefore very timely to fully more research a wider basis for implementing LRS.
The research here is intended to assist transportation agencies before commencing fuller LRS adoption and implementation.

Having personally struggled in the field with many of the issues described herein the last 25 years, this document has offered some opportunity to at least try and put some of these issues and struggles in a wider reference context and methodological framework. The richness of the topic is brought home that even with the length of this thesis, it has provided opportunity to only touch home on many of these key and relevant LRS issues in a very summary way. Such is the challenge of Planning and geographic analysis. Such also is the nature of trying to put a rubric on location and the results of human activities and interaction as a whole.

1.6 Thesis Organization

Brief comment is provided here on the basis for the overall structuring of the thesis and on the design of the chapter-by-chapter structuring.

1.6.1 Higher Level Schema

Some deeper technical consideration was given to the optimal organization of this thesis. A document such as this must itself of course be laid out in “a linear form”. Web-based theses are technically do-able (for example, see the web page of www.spatial-effects), but not within current MIT regulations for final delivery copy. The challenge was here that some issues particularly involve the review of an array of topics around them; the understanding of one topic can be dependent in part on another. Thus, one is challenged to, “break into the circle”.

The approach here therefore breaks away just a little from that at least overtly normally employed. The approach follows an explorative style of research. This basis and approach for this is reviewed in more detail in Chapter 2. The five principal work-steps undertaken involved:

1. Analyzing the experience of others as recorded in a review of published reports
2. Synthesizing the theory behind linear referencing
3. Four more detailed systematically carried out comparative case studies, and
4. Participating in two expert panels, coupled with other supporting field and existing research analysis.
5. Formulating direction for a new OO-based approach.

The emphasis is on highway systems, although the concepts may be applied to other linear features and networks, such as railways, waterways, or pipelines. Current issues and research relating linear referencing for highways with other modes of transportation are described. This thesis addresses the implementation of linear referencing with GIS, but is independent of any specific GIS software (other than that reported in the case studies).

1.6.2 Chapter Review

Chapter 2 provides a review and justification of the selected research methodology and approach. Consideration is made of the selected research methods. Research of research methods for PIS would itself be a very valid research task and thesis topic. The review provided here is
preliminary but is aimed at a synthesis on current practice and provides the framework for the research work subsequently undertaken in this thesis.

Chapter 3 provides a deeper review of the context of LRS, as this has been argued to be key. The field addressed here has a number of wider-ranging elements that are pertinent to its consideration and analysis. Thus, introducing a little more fully the wider academic analysis reference frame to draw on was a task to be wrestled beyond any first chapter. As we seek to best understand and create appropriate models of space, analysis of context is critical. Different frameworks for establishing such order are available. Given the real importance of situational and disciplinary context here, Chapter 3 provides a review of the wider fields that pertain to the analysis of “the LRS problem”. This chapter aims to set and clarify the widest and most appropriate context frame for the subsequent LRS research work. It briefly reviews the subject or human activities and organization and how to date various locationally focused fields or disciplines (Geography, Urban Planning and Transportation) have sought to express and analyze locational issues. As already noted, the background to the field is fairly significant in breadth and scope. An attempt is made to synthesize material from fields relevant to the LRS topic.

Chapter 4 provides an initial introduction to Linear Referencing Systems (LRS), including its history of use, current use, and essential terminology. The LRS overview should hopefully be of interest to both readers more or less experienced in LRS. Given that much attention is being given to LRS currently because of the advent of much linearly generated data and the advent of relatively cheap computer processing systems to process linearly referenced data, brief review of these technologies is given. Chapter 4 includes a brief review of the relationship between linear referencing and GIS, two data management technologies that have converged to provide the most powerful information analysis capabilities. This material is placed in Chapter 4, rather than in the Introduction, as given the importance of the topic a little more detailed treatment is given than might occur in the first introductory chapter. Given the field complexity of LRS terms, as an essential task of this thesis, Chapter 4 provides a full and detailed review of LRS concepts and essential terminology for linear referencing. A full glossary is provided in Appendix A, including the sources used for the definitions.

Chapter 5 provides a review of recent research in LRS. This has mainly focused on the creation of road data models, or, coding schemas. Taking the term “model” in the wider sense to include the coding schemas or transfer standards, the leading six models are briefly reviewed. The intent here is not to repeat the descriptions of the models provided elsewhere, but to provide a brief summary and critique of key features and the current standing of the models.

Chapter 6 provides a review of ten example spatial network definition problems which relate strongly to be able to practically implement LRS in the field. This review is conducted based on the four transportation agency LRS case studies that were carried out without going into the specific details of the coding schema used. Then the chapter presents consideration of ten specific implementation issues relevant to linear referencing, bundling the theory behind each topic area with details from the four DOT case studies agencies. This chapter in many ways is the heart of the thesis and the subject matter. It is in the details described here that the practical field implementation issues and difficulties of LRS occur. While this chapter tries to cover the ten chosen aspects in summary form, this chapter in its entirety may be a challenge to best fully digest at one quick reading. A brief introductory overview of the case studies is given including the main findings from each study.

Chapter 7 summarizes national research on temporal aspects of GIS (TGIS). This is based on the case studies, the activities and results of a NHCRP transportation modal expert panel that was
participated in, and literature research. The intent here is to take a broaden view of LRS needs across transportation modal communities. The goal of this chapter enunciates the main functional requirements that are additionally needed to support multimodal and temporal LRS.

Chapter 8 carries out a more detailed review of the existing road data models. It is based on the initial desktop review of the models carried out in Chapter 5, and the results of the case studies. The chapter attempts to do a more detailed “compare and contrast” of the models, utilizing the direct input of a specially convened panel of the transportation model experts.

Chapter 9 provides a brief critique of institutional issues as they related to LRS. It is noted that no work has been completed previously on LRS institutional issues to date. The focus of the thesis was largely disciplinary and technical in focus, but institutional issues were discerned throughout the case studies and expert panels. The institutional observations also underlie some of the directions for design outlined in the following chapter.

Chapter 10 summarizes the overall findings of the thesis. It includes a summary of the findings on LRS, on doing planning information systems research and on potential new avenues for LRS activities. Next steps in LRS research are identified.

Table 2 below provides a summary of the contents of this thesis.

In summary on the layout chosen, while it may be argued that LRS represents the “simplest spatial case”, the diversity of topics that truly effect its wider analysis and consideration has meant that a diversity of literature and analysis has had to be drawn upon and “framed”. Therefore, in gaining best “handle” on the wider volume of material, it was generally found appropriate to make use of a summary point style and a heavy reliance on diagrams and summary tables in many sections.

Much of the supporting material, including an Annotated Bibliography, a Glossary, the LRS questionnaire, and other material used to support the thesis, are found in the Appendices. A list of Appendices is included with the table of contents. In particular, Appendix G summarizes some “reflective practitioneering” that was completed in the context of the research findings that were gathered in the previous chapters. It provides some summary considerations in terms of network definition, multimodal analysis and temporal considerations. These are based on defining a new concept of network and network elements based on the research carried out in this thesis. Some object-oriented based analysis is used to facilitate the consideration.

Also, given the diversity of topics that relate to LRS and covered in this thesis, references for each chapter and topic are included at the end of that chapter.
<table>
<thead>
<tr>
<th>Chapter</th>
<th>Title</th>
<th>Purpose/Contents</th>
</tr>
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</table>
| 1       | Introduction                               | • Thinking spatially  
          |                                        | • Place of linear analysis  
          |                                        | • Basic LRS method  
          |                                        | • Layout of thesis |
| 2       | Research Methodology and Approach          | • Planning Related Research  
          |                                        | • RM in parallel fields  
          |                                        | • Multi-faceted, layered approach  
          |                                        | • Selected research steps |
| 3       | Epistemology and Ontology                 | • Disciplinary viewpoints on networks  
          |                                        | • Process of Modeling  
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| 4       | Semantics and Technology                  | • LRS terms  
          |                                        | • GIS Methods  
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| 5       | Research                                  | • NHCRP model  
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| 6       | Spatial (Network) Definition              | • Four case studies outlined  
          |                                        | • 10 coding issues  
          |                                        | • Local Roads  
          |                                        | • Mileage Equations |
| 7       | Temporal Issues                           | • Literature Study  
          |                                        | • Case Study DOT's handling of time  
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          |                                        | • Why Model?  
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          |                                        | • Approaches to Institutional Issues |
| 10      | Conclusions                               | • Case Study Review  
          |                                        | • Goals For A Robust LRS  
          |                                        | • Network Coding Recommendations  
          |                                        | • New Ways of Thinking LRS |
1.7 Chapter Summary and Conclusions

The goal of this chapter has been to provide some introduction to LRS and of the issues to be addressed further in this thesis.

1.7.1 Progress Achieved

This chapter introduced the concept of LRS. A brief overview was made of spatial activities and thinking research on the LRS topic was given. The introduction of LRS in Roman times and subsequent use was described. Some of the key terms in LRS were introduced. A list of some of the key highway types was provided, and the challenges faced reducing this to a form that could be used with LRS. The objectives of the thesis are summarized from two perspectives – LRS technical research goals and Planning Research goals.

1.7.2 Ten Key Observations

The ten main observations of this chapter were that:

1. **History of Use**: Linear traversal measurement is an ancient activity. It was originally designed to work on the relatively simple road forms that existed.

2. **Role**: Linear referencing is well established as the principle means by which transportation agencies manage network-related data. Linear referencing is now viewed as just one type of location referencing within a larger location referencing system. The implementation of LRS in GIS has become the normal pathway to an integrated highway location referencing system. Full integration between linear referencing control databases and GIS has become desirable as full-featured display and analysis of current and historical information moves from wishful-thinking to a practical reality.

3. **Research Basis**: Only in very recent times has it been studied more formally and in-depth. It is a topic for which a prior research base has not been firmly established.

4. **Class of Problems**: The study of LRS involves consideration of the class of "messy" spatial problems.

5. **Spatial Varieties**: Transportation highway networks on which LRS are placed come in a variety of real world forms and complexities.

6. **Economic Investment**: There has been significant historical investment by transportation agencies in collecting linearly referenced data.

7. **Technology Development**: This investment continues today with the use of GPS-equipped highway data collection vans. Emerging technologies, new methods of
data collection and the expanding responsibilities of transportation agencies have changed the way the linear referencing is viewed and implemented.

8. **Advantages of LRS:** While there are some disadvantages to LRS, and new technologies such as GPS make available 2D data in an increasingly cheap and accurate form, the use of LRS has intrinsic advantages. The advantages include:

   a) It is generally an intuitive system to use in the field
   b) It pre-assumes existence on the network, so there is not the problem of “snapping” to the network
   c) It allows for data to be collected where there is a change in conditions. Therefore, if the data condition does not change for 101.1 miles, there will only be a 0 mile and a 101.1 offset indicators of change to be recorded in the database.

9. **Data Models:** One of the strengths of LRS is that it readily lends itself to data models. One of the challenges of LRS is that it lends itself to data models. The number of complexities in real world networks has been noted above.

10. **LRS Development:** The design and refinement of linear referencing systems will continue with greater sophistication to meet new objectives. Greater data integration will enable more thorough analyses to improve the decision-making process of where investments are best made in the transportation network to meet various (often conflicting) needs. Linear referencing methods, as one component of robust location referencing systems, will provide an essential framework for development of integrating transportation information systems (ITIS), intelligent transportation systems (ITS), and related endeavors.

To meet DOT stated needs, newly designed applications in LRS, GIS-T, and ITIS must be flexible enough to readily accommodate changing software and data collection techniques. Software itself is evolving towards a fully open architecture through object linking and embedding such that sub-applications are modular. Preserving the potential for future growth requires an ability to accommodate change. Arguably, this decade has marked a fundamental transition where GIS and LRS practices no longer dominate transportation data management, but have become subservient tools beneath greater visions of “ITIS”.

The further goal of this thesis is to present “a more complete understanding of events around us”, or at least one aspect of them, (as indicated by Hawking in the quote below). Gaining a fuller basis for understanding LRS is one element of daily search to find spatial order for our existence. Understanding LRS – and “how to understand how to understand LRS”, can help us better understand a wider class of planning and spatial related problems.

"So even if we do find a complete set of basic laws, there will be still in the years ahead the intellectually challenging tasks of developing better approximation methods, so that we can make useful predictions of the probable outcomes in complicated and realistic situations. A complete, consistent theory is only the first step: our goal is a complete understanding of events around us, and our own existence".

Hawking, S. 1988, p.168
1.8 Chapter References


2 Research Methodology and Approach

"The problems that the professional practitioner – such as lawyers, doctors or engineers – face are rarely straightforward and clear. They are frequently complex and lack "right answers". Skillful professional practice often depends less on factual knowledge or rigid decision-making models than on the capacity to reflect before taking action in cases where established theories do not apply. Yet most professional schools only teach students standard scientific theories and how to apply them to straightforward problems – and so fail to equip future professionals with the skills they need to deal with the difficult problems of the real world". (Schon, 1983)

2.1 Introduction and Purpose

Twenty-five years ago researchers were able to write, "On transport forecasting a tremendous amount of both theoretical and empirical work has been done" (Schuster, H. 1974). The urban transportation planning systems process (or the UTPS process) was created in the 1950's (Eno Foundation, 1956). Following this, in the 1960's several scores of research papers would be published each year on trip generation and travel forecasting methodology improvements. Focus on such topics increased in the 1970's to the present day. A total of probably several thousand papers produced by this date on this form of network modeling. Such research would often be written up in the Highway Research Record (HRR) in the 1960's, which later became the Transportation Research Record. (For example, see Highway Research Board, 1968).

Many modern-day researchers in these areas are not aware of the many excellent (and still pertinent) papers that were produced in the 1960's, and often exemplified in the HRR.\(^3\) Much subsequent systems and planning research was based in and around such models. There were occasional down-swings in the popularity and prevailing academic viewpoint, as evidenced by Douglas Lee's Requiem for the Large Scale Models paper, (1974). However, the overall bias of much transportation research to this focus area has remained. Many university theses have been based on this general topic area. Research work until this day still tends to more naturally focus on trip generation and trip forecasting and assignment. A total of several thousand academic papers and contributions have been made in this area, including approximately 80 from MIT alone in the last decade or so.

Topics such as trip generation and assignment, while important transportation topics, do not exclusively focus on some of the core of the current transportation industry's most critical practical needs. Analyses undertaken of what for example actually a state DOT undertakes, trip generation and flow modeling are actually a relatively small proportion of their critical work areas (Lewis, 1997, Lewis and McNeil, 1986). However, it has been very clear the real needs of modern-day DOTs are managing the infrastructure. DOTs have passed from a central goal of creating the infrastructure - with the construction of the interstate highway system - to managing

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\(^3\) This will be similarly also noted within Chapter 3. There note is made that much excellent research work done on the topic of geographic analysis such work has likewise poorly referenced by modern-day researchers. Such work can be quite difficult to directly access, even through better libraries appears and journals over 25 years old, even when microfiched. A lot of this work In terms of clarity and exposition is well worth reference.
the infrastructure. Managing transportation infrastructure requires codifying knowledge of networks — and the use of techniques such as linear referencing systems. The algorithms exist for many commercial applications — such as street or address finding — but the data does not in an integrated form.

A linear referencing (information) system can be considered a Planning Information System (PIS) (or spatial – geographic - information systems) when it is used to planning decisions, or an Engineering Management Information Systems (EMIS) when it used to support engineering decision-making. Research and consideration of existing methodologies was thus needed on both these fields. Given that a standard scientific approach (in line of Schon’s comments above) was not available, this was practically a major issue for this thesis research. Reference to the latest “best practices” in information technology was appropriate. It was also appropriate to review some of the early seminal works that help create the academic field of transportation trip modeling, which was later to create so much additional research and activity. In fact, wider reference to the 1960’ academic research was fruitful as it revealed a few of the pieces of research that had been done on network characterization, so useful in considering LRS.

In summary, in research terms the LRS field is new, with relatively little established precedent. Thus, a suitable approach needed to be crafted, drawing both from existing available tools in parallel fields of inquiry, and also the particular characteristics of this research field. This chapter reviews the work undertaken to craft such an appropriate approach. This includes:

1. **Research Method (RM) Approaches:** A consideration of PIS and EMIS research issues and approaches, including context-driven and practitioner-based research.
2. **Practitioner Focus:** Some further consideration of the problem of doing practitioner-based research.
3. **Alternate RM:** Alternative available research methodologies (including, for example, the waterfall and the amended waterfall approaches), and
4. **Selected RM:** The selected research methodology, which is described in terms of both research tasks and “research tracks”.

Obviously, as a first endeavor in this particular area it may be left to others to further develop and refine such approaches.

### 2.2 LRS Research Needs

There are a number of alternate LRS designs that may be potentially quickly adopted by a DOT. Appropriate and successful adoption of any one LRS is likely to benefit from a consideration of several factors. These include the following principal two:

1. **User Needs:** An appropriate consideration of individual detailed agency technical needs, and,
2. **Best Practices:** Wider industry field and software tool “best practices”.

There have been no agency case studies of “less successful” LRS adoption in the US (e.g., earlier efforts in Iowa DOT). Several of these such LRS efforts have had to be soon re-engineered. Little formal reference on these can be given, as failure, absolute or relative, is rarely written-up.
LRS presents both technical and institutional challenges. Gaining agency consensus on appropriate LRS requires a real and focused measure of DOT top-level management support. Technical and institutional review of LRS has been typically hampered within the organization by organizationally embedded and technically divergent views. Many of these issues may be linked to:

1. **Vision**: A lack of fuller appreciation of the role, importance and technical nature of LRS; and
2. **Language**: More particularly, to key differences in the use of LRS-related nomenclature.

In a wider sense LRS implementation has much akin with GIS implementation, of which it is essentially a part. Bijan Azad in his excellent PhD thesis on GIS implementation (Azad, 1998) gives a well-researched summary review of some the research models that have been applied to spatial (GIS) case study analysis. He in particular reviews *factor research models*, and, *process research models*.

If this was applied to the LRS field, in short factor analysis might for example attempt to determine associations between various aspects of LRS implementation (e.g., leadership, use of Linear Reference Method (LRM 1, LRM2, etc.), and, say, resultant progress. Process research would in short focus on the details of the LRS implementation process — that is “videotaping” the process of LRS implementation in attempt to lay bare details, which by examination may be made of aspects of the process.

The previous research on LRS has essentially nearly all occurred in the 1990’s and has essentially largely focused on *LRS data models*. It seems that the basis for a unified modeling system for LRS was the “El Dorado” that most researchers to date have focused their principal energies on (Butler, Vonderohe, etc). Fundamental consideration of transportation indicates that such research faces these issues well known to transportation practitioners:

1. **Complexity**: The complexity of transportation networks, and
2. **Diversity**: Transportation was not ‘one information community’ but in fact several information communities, e.g., for:
   a. Modal areas, such as for:
      i. Highway
      ii. Transit
      iii. Air, etc
   b. Special interest areas, such as for ITS.

These considerations would then *a priori* indicate:

1. **“Many Models”**: There was “no one right approach” to implementing LRS, and
2. **Toolboxes**: It was in fact a skill and an art that needed further research on the core components to lay bare the “tool-box” that field implementers had to use and adapt.

It was also a key observation that many of those responsible for LRS research in the 1990’s had relatively little, direct, field experience at that time (and, thus the detail) of using or “practitioner” LRS. Conversely, across the whole of the United States, there were very few individuals left in state DOT’s who understand their own LRS’s. DOT’s depend typically on consultants to get up to speed with their in-house systems (that had themselves often been
developed by consultants). There was thus a lot of good thought, but little solid field research basis, for much of the LRS analysis that was undertaken in the 1990's.

2.3 The Need for Practitioner-Focused Research

The work of Don Schon, former Department of Urban Studies Ford professor at MIT, has been instrumental in framing the research approach developed for this thesis. Don, who sadly died in 1997, fittingly gave one of his last major contributions in framing a colloquium at MIT in 1996 on, “High Technology and Low Income Communities”. An example of practitioner transportation network research is provided in a review of transportation network models provided for the World Bank (Lewis, 1991).

Schon had earlier given a seminal call to the field when he wrote in his seminal work, "The Reflective Practitioner". As that work has had a major influence on the research frame adopted for this thesis, four quotes are drawn from his work. He wrote:

"But, as we have come to see with increasing clarity over the last twenty years or so, the problems of real-world practice do not present themselves to practitioners as well-formed structures. Indeed, they tend not to present themselves as problems at all by as messy, indeterminate situations". (Schon, 1983).

It is argued in Schon’s words that the real world we are dealing with here, LRS, is “messy”. A part of thesis will go to demonstrate in detail some examples of the “messiness”. Schon goes on to further state:

"Civil engineers, for example, know how to build roads suited to conditions of the particular sites and specifications. They draw on their knowledge of soil conditions, materials, and construction technologies to grades, surfaces and dimensions. When they must decide what road to build, however, or whether to build it at all, their problem is not solvable by the application of technical knowledge, not even not solvable by the application of technical knowledge, not even by the sophisticated techniques of design theory. They face a complex and ill-defined mélange of topographical, financial, economic, environmental, and political factors. If they get a well-formed problem matched to familiar theories and techniques, they must construct it from the materials of a situation that is, to use John Deweys’ term ‘problematic’. And the problem of problem setting is not well formed.”

Much that is formally taught in transportation or planning curricula rightly often address the teaching of methods that can underline multiple areas of professional practice. The base underlying concepts of LRS are for the most part exceptionally mathematically simple. However, the detail and practice of LRS has proved exceptionally difficult to successfully implement if the field. Many have been educated with “rigor”; educating with “relevance” often does require gaining particular working knowledge of the domain, and its intricacies, but then further the ability to deal with real world situations. LRS is an area that requires skills in dealing with second and third levels of details, “exception handling, and real world eventualities.

While here we are considering the issue of constructing information systems about roads, many of the concerns of Schon are still applicable. Rather than “face an ill-defined
mélange of topographical, financial, economic, environmental, and political factors”, we have face “an ill-defined mélange” of unclear joint conceptions of the real world, different lineages of analytical viewpoint, and differing user community needs. Schon points further points how our “vocabulary” affects matters:

*When a practitioner sets a problem, he chooses and names the things he will notice. In his road-building situation, the civil engineer may see drainage, soil stability, and ease of maintenance; he may not see the differential effects of the road on the economies of the towns that lie along its route. Through complementary acts of naming and framing, the practitioner selects things for attention and organizes them, guided by an appreciation of the situation and gives it coherence and sets a direction for action. So problem solving is an ontological process – in Nelsons Goodman’s memorable word, a form of worldmaking”.

**Epistemology** is defined here as, *the branch of philosophy that studies the nature of knowledge, its presuppositions and foundations, and its extent and validity.* Clearly a consideration of epistemology and epistemological issues are first important in “worldmaking”. *How* we define and view the LRS problem is clearly very important to it our handling of it.

**Ontology** can be defined here as, “an explicit formal specification of how to represent the objects, concepts and other entities that are assumed to exist in some area of interest and the relationships that hold among them”. The general ontological arguments and processes described by Schon are in fact at the core of the thesis; that is, how we conceive of LRS reflects how we handle and model it. Fonseca and Egenhofer (1999) have defined the need for an ontology-driven GIS (what they call, “ODGIS”). They state that:

*The mapping of multiple ontologies onto system classes was done through object-oriented techniques using multiple inheritance. This kind of mapping allowed partial integration of information when completeness was impossible.*

This line of concern will be a little further explored in Appendix G. In his later work, *Educating the Reflective Practitioner*, Schon notes:

*Technical rationality, the schools prevailing epistemology of practice, treats professional competence as the application of privileged knowledge to instrumental problems of practice. The schools normative curriculum and separation of research from practice leave no room for reflection-in-action, and thereby create – for educators, practitioners and students – a dilemma of rigor or relevance. (Schon, 1987).*

The focus of Schon’s work does indeed more onto the topic of educating the professional. (In short, he proposes a “virtual world” - sometimes called a “microworld”, by other authors who took and developed his concepts - that is a “constructed representation of real world”).

Others have subsequently tried to address the problem of *how* to frame research that bridges the divide of “rigor or relevance”. Richmond, drawing in part on his PhD thesis work for Schon, as well as work as a transportation practitioner in Los Angeles, in a
seminal paper, outlines the shortcomings of current systems analysis approaches in transportation. He proposes an alternative form of systems research, involving in part ad hoc approaches, and multi-disciplinary, multi-party input and interaction (Richmond, 1989). This thesis in part carries forward his proposal.

The fuller importance of Context has increasingly become more widely realized as an important academic discipline. The Second “International and Interdisciplinary Conference on Modeling and Using Context” was held in Trento, Italy, 1999. Of the over 50 papers presented at that conference many have potential longer-term implications for the furtherance of the work here, for example in terms of research methodology, dealing with semantic issues and the appropriate design of software in cross-disciplinary fields.

2.4 The Problem of Executing Practitioner-Based Research

Much of traditional academic research (at least at the doctoral level) has often focused on making a marginal improvement to an existent theoretical domain. In this typical research schema, the latest “edge” of research is identified. This research will have an established literature typically supporting the acquisition of the research point reached previously to date. New doctoral work has typically provided extensions to existing models or provided modeling approaches for particular, special case, circumstances. (A more enlightened delivery of such approach is provided by Srinivasan, 2000). An intensity of understanding and effort in execution may be required to push or expand the envelope of research if it developed a frontier where others had previously stopped. An efficiency is gained in delivery as there is less need to re-identify and then complete a framework for the synthesis of the field itself for the first time.

For example, in transportation network analysis to date, the last 30 years have in some large part been concerned with research to make marginal improvements to algorithms to analyze transportation network flows. As a reflection of this, the recent book “Network Infrastructure and the Urban Environment: Advances in Spatial Systems Modelling” (Lundqvist, Mattsson, and Kim, 1998) is essentially concerned with flow models, interaction models, and land use modeling. Despite the title the book – and much research over the last 30 years – the transportation research community has not more rigorously or fully considered the set-up and analysis of the infrastructure on which flows were being optimized. Traditional research has typically in a simple form taken a linear, “additive” approach, as indicated in the Figure 2 below.

![Figure 2 Linear Extension Research](image)

In designing an information system, one can consider different data modeling levels that exist between the real world and physical implementation in a database or application.
The levels briefly summarized are as follows:

1. **External**: Potential users define the subset of the real world that is relevant to their needs.

2. **Conceptual**: A concept or abstraction of the real world, provided to synthesize understanding. It is concerned with the information content, not physical storage; thus the same conceptual model may have alternate physical models that implement it. Conceptual models often use entity-relationship modeling techniques.

3. **Logical**: This is a transfer of the conceptual model into a model form that can be directly programmed. Three different logical model forms that have been traditionally used are hierarchical, network and relational. This level is concerned with tables and data records.

4. **Internal**: This level is internal to the computer, and may be concerned with storage devices, file pointers, access methods, and locations of data.

Figure 3 summarizes these data modeling levels.

**Figure 3 Data Modeling Levels**

The established data modeling levels correspond in some rough manner to the levels of abstraction that need to be typically defined in practitioner-level research. In fact the practitioner level research focuses very much on the interaction between the External and Conceptual levels of modeling, arguing that until this are formally best established, the logical and internal modeling cannot be appropriately completed.
Figure 4 denotes the role of practitioner-based research. Obviously this review is presented at a high-level of generalization. However, a clear implication of this sketch is that typically such research involves gathering, ordering, and processing a much wider body of knowledge than much typical theory-developing or extending research. This is typical both where, 1) there is limited establishment of prior theory or academic analysis frame, and, 2) consideration of a professional field of practice is being researched. Obviously, such research may not be best conducted by those without strong prior field exposure, explaining in part why many young academics focus on theory extension and why many real world practical problems, such as LRS, which yearn for more formal consideration, have been ignored. While fuller discourse is not provided here, it is also explains why “wrestling the subject” and the research approach was a key issue for PIS doctoral theses, such as more recently completed by Azar (1995), Azad (1998) and Evans (1997).

**Figure 4 The Contribution of Practitioner Based Research**

As noted in the Introduction to this Chapter, research on transportation trip generation and flow modeling has progressed significantly now. There is very well-established precedent for conducting such research in doctoral terms. In some universities one has been advised to take this path if one wants a quicker exit to the door of graduation (possibly, a typical issue between relative economy and relative relevance). In practitioner terms, it seems the real needs are in the field are of examining transportation information infrastructures. The cost of this is that this is little if any established precedent for conducting research in this area. No prior thesis work at all has been conducted in this area compared to the at least several hundred thesis written on transportation trip generation and flow models. Therefore, as with some of the more ground breaking work done in the 1950’s and the 1960’s in transportation modeling, basic spadework needs to be done here, including on adoption and justification of research approach. This can be the added real cost of “practitioner research".
2.5 Research on Research Methodologies

A review was made on research on methodology appropriate for a fuller consideration of the LRS topic in a practitioner context. The literature of possible relevance in a wider context was quite large to draw on, but much more limited especially when focused more specifically on EMIS and PIS. Very few researchers seem to have fully honed in on this topic, in part perhaps because of some of the reasons outlined very briefly above.

The leading thinker on research methodologies relevant to this domain – and in promoting the importance of research methodologies - in the 1990's has been Yoram Reich, formerly of Carnegie Mellon University and now of Tel Aviv University. (Reich, 1992, 1994 and 1995). A debt here in this research effort is owed to his prior field contributions. Reich has particularly focused on engineering design and analysis (what is referred to as “EDAM” – Engineering Design, Analysis and Manufacturing). He contends that EDAM research method framing has often been poor to date.

Reich summarizes that at a first level or layer there are two important worldviews in framing research methodology. These are Scientism and Practicism, the former stressing understanding and the latter stressing practical relevance. Schon's view coincident with Practicism. The differences between the worldviews are summarized in Table 3.

Table 3 A Summary of Two Worldviews

(Reich, 1994, who adapted from other sources)

<table>
<thead>
<tr>
<th>DIMENSION</th>
<th>SCIENTISM</th>
<th>PRACTICISM</th>
</tr>
</thead>
<tbody>
<tr>
<td>Researchers relationship to setting</td>
<td>Detachment, neutrality</td>
<td>Immersion</td>
</tr>
<tr>
<td>Validation basis</td>
<td>Measurement, logic, reliability, external validity</td>
<td>Experiential</td>
</tr>
<tr>
<td>Researchers role</td>
<td>Onlooker</td>
<td>Actor</td>
</tr>
<tr>
<td>Source of categories</td>
<td>A priori</td>
<td>Interactive emergent</td>
</tr>
<tr>
<td>Aim of inquiry</td>
<td>Universality and generalizability</td>
<td>Situational relevance</td>
</tr>
<tr>
<td>Type of knowledge acquired</td>
<td>Universal, theoria, precise, causal, cumulative, 'reductionistic'</td>
<td>Particular, praxis, imprecise, multiple causation, problematic, holistic</td>
</tr>
<tr>
<td>Nature of data and meaning</td>
<td>Factual, context free</td>
<td>Interpreted, contextually embedded</td>
</tr>
<tr>
<td>Status of science as a field of knowledge</td>
<td>Privileged, progressive, autonomous</td>
<td>Not separated from other fields of knowledge</td>
</tr>
<tr>
<td>Aims of science</td>
<td>Prediction and control</td>
<td>Promotion of human development</td>
</tr>
</tbody>
</table>
Reich argues that by consideration of these “worldpoints” one is better able to consider techniques and research methods to achieve a particular research objective. He also argues that “Scientism” is the model which has driven much contemporary research methodology, and most researchers seem to subscribe to some form of it. Reich however points out that the “reflection-in-action” (that Schon earlier analyzed) is “fundamental to the successful practice of different practitioners” (Reich, 1994).

Smyth (1998) points out that when we are modeling geographic space (such as for LRS) we are in fact creating “microworlds”.

The fuller distinctions between Scientism and Practicism, and the positions various commentators have taken on them are not traced out here within the current study. However, clearly, the field of Planning and related professional disciplines, dealing with Schon’s “messy data”, have strong case to veer towards field Practicism.

At a second level or layer, whatever initial higher worldview is taken, Reich indicates that there are “heuristics”, (that is, “lines of analysis” or perspectives) that maybe taken. Table 3 summarizes some of the key heuristics proposed.

Table 4 Analysis Perspectives

(Adapted from, Reich, 1994)

<table>
<thead>
<tr>
<th>#</th>
<th>PERSPECTIVE OR HEURISTIC</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Cognitive Science</td>
<td>Informed by insight from psychology. The work on case-based reasoning originated from this perspective</td>
</tr>
<tr>
<td>2</td>
<td>Decision Science</td>
<td>Attempts to argument the deficiencies of human decision-maker, such as psychological biases</td>
</tr>
<tr>
<td>3</td>
<td>System Science</td>
<td>Attempts to view a project within a larger system that is expected to function. This can lead to the development of embedded systems</td>
</tr>
<tr>
<td>4</td>
<td>Software Engineering</td>
<td>Attempts to create software for doing specified tasks. Exploratory programming is a prime concern.</td>
</tr>
</tbody>
</table>

A third level in Reich’s schema deals with specific issues such as the methods for evaluating hypotheses and the criteria for such evaluations. Table 4 summarizes the levels.

Reich further notes a research methodology will be comprised of combinations from different levels (e.g., Scientism-Cognitive Science, Scientism-Formal methods, etc.). It is noted that few of the combinations involving Practicism have been tested as yet.
Table 5 A Layered Model of Research Methodology

(Adapted from Reich, 1994).

<table>
<thead>
<tr>
<th>#</th>
<th>LAYER</th>
<th>EXAMPLES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Worldviews</td>
<td>Practicism, Scientism</td>
</tr>
<tr>
<td>3</td>
<td>Specific issues</td>
<td>Formal representation, Parsimony, Practical, Relevance</td>
</tr>
</tbody>
</table>

2.6 Research Method (RM) Selection

This section considers the overall adoption of a research methodology.

2.6.1 RM selection Criteria

Reich suggests some criteria for assessing the quality of research methodologies. These include:

1. Parsimony
2. Clarity
3. Power or range of applicability
4. Completeness
5. Correctness
6. Commercial success

What Reich has not pursued to date further is how one in more detailed guidelines for how one structures research and advice on how best to pick the layer combinations.

It has been argued that the nature of the topic chosen here lends itself to Practicism. A decision needs to be made on what research heuristic to apply. In fact, much research seems in RM to apply one heuristic. This would seem to follow the criteria of "Parsimony", but not necessarily give "Completeness" or "Correctness". Suppose for example it is decided to research a GIS issue through the use of case studies (a
"Cognitive Science" heuristic). Then suppose that for one reason or another (including, but not restricted to, the possibility that the case studies were not well designed, selected, executed, or, for reasons outside of the control of the researcher), "successful". The researcher is often faced with practical pressures to report a successful research project when in fact the sought after end-goal may or may not have been gained. If the goal of much research is first "understanding", but then ultimately problem solving, it is unlikely that research focused on one combination of research layering would "solve the problem"—though it might greatly increase the base of understanding in one dimension, which in concert with work with others, may ultimately "solve the problem".

However, for the practitioner, practical competence involves in the field a drawing together of many design elements. In many professional disciplines, such as Planning, this involves drawing together various disciplinary viewpoints. The tenet taken here is that adopting one research layer combination might provide some useful insights, but might not best constitute the basis for some form of a potential effective contribution to in the field, end, professional practice.

2.6.2 Adopted Outline RM Approach:

One RM may have limited ability to cognize and develop in meaningful terms a practitioner area of research. Therefore, in selecting a research methodology here, the layered approach was adopted to combine a Practicism worldview with four research heuristics. The four principal heuristics chosen from the Reich framework were:

1. System Science
2. Cognitive Science
3. Human Centered
4. Software Engineering

The defining of these four categories within the context of the research undertaken may be taken to be somewhat arbitrary. Given all the above methodological considerations, a set of five basic tasks was set for this research. A sixth set task was synthesis. These tasks are summarized in Table 6.

The research framework adopted was in fact and extension and enhancement of the approach of the authors’ MIT SM/Civil Engineers thesis (Lewis, 1986). That work also involved a sequential but iterative process, reducing data from desktop exercise, field and expert data collection and software tool building.

2.6.3 Interaction Between Layers or Tasks:

One item not explicitly covered by Reich is the need in practitioner-focused research is to undertake feedback and interaction between the research layers and activities. The presentation of the results of research has historically always of necessity presented in a “linear fashion”. However, the research itself is in many areas, an iterative process of research, digestion and refinement. Real world or practitioner focused problem solving and software development has historically often been formally “best-practice” conducted in an overall frame of “waterfall fashion” (see Figure 5, below). This was originally described by Royce (1970). While more
regularly applied to software project execution, it can be applied to various other types of project development. Each phase of the waterfall corresponds to an activity.

Table 6  LRS Research Tasks

<table>
<thead>
<tr>
<th>TASK #</th>
<th>HEURISTIC</th>
<th>RESEARCH TASK DESCRIPTION</th>
<th>PURPOSE</th>
<th>KEY SUB TASKS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>System Science</td>
<td>Basic desktop review of LRS and disciplinary perspectives</td>
<td>Overview of LRS experience and practice</td>
<td>Ext review of disciplinary literature</td>
</tr>
<tr>
<td>2</td>
<td>Cognitive Science</td>
<td>Four detailed on site DOT LRS case studies</td>
<td>Systematic review of LRS issues; main common issues</td>
<td>Design Questionnaire Visit agencies Synthesize results</td>
</tr>
<tr>
<td>3</td>
<td>Human Centered Cognitive Science</td>
<td>Transportation Field Expert panel</td>
<td>Transportation field requirements (e.g., modal, time)</td>
<td>Gather field practitioners to express views</td>
</tr>
<tr>
<td>4</td>
<td>Human Centered Systems Science</td>
<td>LRS Model Expert Panel</td>
<td>Model overlaps and similarity; gain consensus on core model</td>
<td>Create common base analysis problem Gather model experts Interact</td>
</tr>
<tr>
<td>5</td>
<td>Software Engineering</td>
<td>Desk exercise, OO Approaches</td>
<td>Improved software and coding approaches</td>
<td>Research best practice techniques Investigate possible basis for new approach</td>
</tr>
<tr>
<td>6</td>
<td>Human Centered</td>
<td>Reflection</td>
<td>Synthesis</td>
<td></td>
</tr>
</tbody>
</table>
Figure 5 Waterfall Method

![Waterfall Method](image)

Figure 6 shows the waterfall method applied to the creation of a Geographic Information Systems Plan.

Figure 6 Waterfall Method Applied to the Creation of A GIS plan

![Waterfall Method Applied to the Creation of A GIS plan](image)

The waterfall process is a linear analysis method. In reality, most planning related issues are complex issues and “information feedback between phase is necessary to incorporate upstream corrections based on discoveries found downstream” (Muller, P-A, 1997). Thus, an iterative process is often more optimal. Conklin and Weil call this type of problem “Wicked Problems”, and state, “traditional tools and methods are suitable only for solving tame problems. Until now,
there has been nothing available to structure the messy, opportunity-driven process that needs to take place” (Conklin and Weil, 2000). While they do not describe it, there is in reality a spectrum of problem types between “Tame Problems” and “Wicked Problems” in research and projects in the spatial domain. Their wicked problems as they indicate strongly relate to the class of problems Schon called the “messy class”.

Figure 7 below shows an example of the amended iterative waterfall development method. This approach in outline was felt applicable for this research and many other projects in the spatial domain.

**Figure 7 Example of Amended Waterfall Method**

When the process is highly iterative — such as in building a software prototype — that is the modifications between steps are not relatively small, the waterfall approach is replaced by the Iterative Process. The iterative process or method is based on the evolution of measurable and executable steps towards a stated research or project goal. Taken to its full, in conceptual terms, the approach almost follows a military style of “tackling a problem”. While this may seem to overdevelop the point, in fact of course many systematic approaches, including systems engineering, the waterfall approach, and of course as LRS itself, have a very clear lineage in military planning. For example, the key steps may be seen as:

1. **“Mission and Target Selection”**: The high-level aims of the thesis are articulated and refined.
2. **“Target Appraisal”**: A step-back from the topic (almost to a “birds-eye view”) is taken to articulate, as clearly as be done within reasonable space, why almost a priori this is a richer topic, on both epistemological and semantic grounds.
3. “Campaign Strategy”: The challenge of how to research the issue is looked at a fundamental issue in its own right.
4. “Tactics”: A research framework is laid out.
5. “Target lock”: Goal fuller definition: The topic area is laid out in more detail (than was appropriate upfront).
7. “Initial Engagements”: Four case studies are undertaken.
8. “Campaign Review”: A review is made of work to date by high-level and specialist experts.
10. “Gains and Losses Accounted”: What was gained or lost by the strategies and tactics employed is assessed.

The research topic here involved a number of tasks (e.g., LRS Case Studies and expert panels,) that could not be readily redone once undertaken, while others could at the margin be refined (e.g., object oriented design). The research thus involved an iterative waterfall method, where some steps allowed for relatively little iteration, others more.

The following sections review some of the particulars of each main work task areas completed.

2.7 Task 1: Field Disciplinary Review

This is defined here in Reich’s schema as a “System Science” heuristic task. (This helps a relevant nomenclature, literature, approach, etc). Adopting the “Practicism” worldview indicated that here that as a key attribute the research as, “Not separated from other fields of knowledge”.

The purpose of this task was to:

1. Define the background to the problem in systems terms in a little detail
2. Define the “perspectives” or worldviews that various field disciplines (“epistemologies”) bring to LRS.
3. Determine the potential contributions these fields may make from their prior activities or literature.
4. Provide a synthesis of such information.

This task could largely be practically completed as a “desk-top exercise”, utilizing field knowledge of the fields that are involved in locational analysis. Steps to completing this task included reviewing the wider literature and disciplinary perspective relevant to LRS.

The interdisciplinary nature of GIS and related areas has long been realized and often commented on in the field and in the literature in passing. However, a first fuller attempt at identifying the contributions of the various disciplines within an academic and historical context such as attempted here has not been identified in the literature.

Chapter 3 describes the work that was carried out under this task.
2.8 Task 2: Case Studies

This is defined here as a "Cognitive Science" task. The Practicism worldview implied immersion in the case studies and the nature of the data being gained being interpreted contextually.

The purpose of this task was to document detailed agency experience of LRS around some common issue points.

The wider Cognitive Science setting, the technical role and better practices for the set-up of the Case Studies is provided here in a little more detail. The reasons for this are:

1. It was a focus of much of the work carried out here
2. It has been the focus of much previous PIS/GIS research

James Odell in the Introduction to "Cognitive Patterns: Problem Solving Frameworks for Object Technology", states that:

"As systems became more complex, the human limitations to comprehending systems requirements became more evident. Since we cannot develop appropriate solutions if we do not understand the problem, human understanding is the key ingredient". (Odell, J, 1992).

Cognitive Science is "the scientific study of the aspects of mind which are governed by a finite set of rules for the formation, transformation, and destruction of information". While this thesis is not bound in Cognitive Science, case based reasoning has been most strongly developed thorough the cognitive sciences. Cognitive Science has a particular method for modeling and "for solving a problem".

Much research carried out at the doctoral level research into PIS and GIS have focused on the use of case studies (see, for example, Evans, 1997, Azad, 1998, and Azar, 1998). However, little formal justification or consideration of the appropriateness and completeness of the case study approach was given, though Azad treats this topic in a little more detail.

Leader case study methodologist have described a number of has identified some specific types of case studies (Yin, 1993, Stake, 1995). These include:

1. Exploratory: Sometimes considered as a prelude to much social research
2. Explanatory: May be used for doing causal investigations
3. Descriptive: Require a descriptive theory to be developed before starting the project
4. Intrinsic: When the researcher has an interest in the case
5. Instrumental: When the case is used to understand more than what is obvious to the observer
6. Collective: When a group of cases is studied.

In all of the above types of case studies, there can be single-case or multiple-case applications. It would seem that much of the PIS case study research to date has been exploratory and collective. Case study research is not "sampling research". However, selecting cases must be done so as to maximize what can be learned in the period of time available for the study.

Yin (1994) identified six primary sources of evidence for case study research. The use of each of these might require different skills from the researcher. Not all sources are essential in every case.
study, but the importance of multiple sources of data to the reliability of the study is well established (Stake, 1995; Yin, 1994). The six sources identified by Yin (1994) are:

1. Documentation
2. Archival records
3. Interviews
4. Direct observation
5. Participant observation, and
6. Physical artifacts.

The case study experts state that no single source has a complete advantage over the others; rather, they might be complementary and could be used in tandem. Thus a case study should use as many sources as are relevant to the study. Table 6 indicates the strengths and weaknesses of each type.

Table 7 Types of Evidence
(Adapted from: Yin, 1994, p. 80)

<table>
<thead>
<tr>
<th>Source of Evidence</th>
<th>Strengths</th>
<th>Weaknesses</th>
</tr>
</thead>
<tbody>
<tr>
<td>Documentation</td>
<td>Stable - repeated review</td>
<td>Retrievability - difficult</td>
</tr>
<tr>
<td></td>
<td>Unobtrusive - exist prior to case study</td>
<td>Biased selectivity</td>
</tr>
<tr>
<td></td>
<td>Exact - names etc.</td>
<td>Reporting bias - reflects author bias</td>
</tr>
<tr>
<td></td>
<td>Broad coverage - extended time span</td>
<td>Access - may be blocked</td>
</tr>
<tr>
<td>Archival Records</td>
<td>Same as above</td>
<td>Same as above</td>
</tr>
<tr>
<td></td>
<td>Precise and quantitative</td>
<td>Privacy might inhibit access</td>
</tr>
<tr>
<td>Interviews</td>
<td>Targeted - focuses on case study topic</td>
<td>Bias due to poor questions</td>
</tr>
<tr>
<td></td>
<td>Insightful - provides perceived causal inferences</td>
<td>Response bias</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Incomplete recollection</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reflexivity - interviewee expresses what interviewer wants to hear</td>
</tr>
<tr>
<td>Direct Observation</td>
<td>Reality - covers events in real time</td>
<td>Time-consuming</td>
</tr>
<tr>
<td></td>
<td>Contextual - covers event context</td>
<td>Selectivity - might miss facts</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Reflexivity - observer's presence might cause change</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Cost - observers need time</td>
</tr>
<tr>
<td>Participant</td>
<td>Same as above</td>
<td>Same as above</td>
</tr>
<tr>
<td>Observation</td>
<td>Insightful into interpersonal behavior</td>
<td>Bias due to investigator's actions</td>
</tr>
<tr>
<td>Physical Artifacts</td>
<td>Insightful into cultural features</td>
<td>Selectivity</td>
</tr>
<tr>
<td></td>
<td>Insightful into technical operations</td>
<td>Availability</td>
</tr>
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</table>

Some further analysis of the role of case studies is made in the conclusions of the thesis.
2.8.1 Factors in Choice of Case Studies

The four detailed DOT case studies in this thesis were selected as leading indicators of the methods and techniques of linear referencing, and for how they have addressed specific linear referencing issues and problems. The focus was on state Departments of Transportation (DOTs), given their leading role as practitioners of linear referencing. Further criteria for selecting the case studies is discussed below. While it is difficult to capture the representative experience of all state DOT’s with four case studies, the selected case studies do serve well to provide ample material representative of current practice in linear referencing.

The objective behind selecting the four representative DOTs was to provide an analysis of issues from which other transportation agencies, large and small, could learn. Although the general design and operation of LRS is paramount, the planning, policy, and implementation tasks were also key subject areas. New techniques in data collection, data warehousing, integrating transportation information systems (ITIS), and the ability to analyze and distribute information simply cannot be ignored. Indeed, GIS-T and ITIS applications built even within the past decade can substantially benefit from these on-going revelations.

Several factors were considered for the selection of the four case studies. Of course, one of the driving issues was the agency’s willingness to participate. Many of the states considered had champion projects to highlight before the transportation community, while others were deeply involved in project development and unfortunately unable to assist in this research at this time. There was also interest in assessing implementations in different geographic areas, and to assure variation in the size, extent, and level of use and general nature of the transportation network. All of these issues have directly impacted LRS development and implementation. As well, it was considered desirable to select case studies whose systems had not been widely reported elsewhere, so as to provide the most new information to the transportation community.

As discussed above, there are several linear LRS methods and techniques that may be blended to provide the best service for a given transportation agency. These methods directly affect the ease with which traversals are updated, the types of historical data that may be stored and retrieved, and how different infrastructure components are recorded.

Other more detailed technical functional characteristics used to select the case studies included:

1. Type(s) of linear referencing methods in use: traversal-milepoint, link-node, or reference point
2. How special cases are handled: ramps, divided highways, one-way pairs, etc.
3. Extent of roadways implemented: state system, ramps, local roads, etc.
4. Support of multiple linear referencing methods
5. Detail and variety in how traversals are defined (e.g., a traversal organization scheme)
6. How historical data are managed (e.g., due to realignments, new roads, etc.)
7. Attribute storage schemes (i.e., table structures)

Equal to these functional characteristics are the managerial policies necessary during LRS implementation. For example:

1. Level of GIS implementation (use of different vendors preferred)
2. Level of data integration through linear and other location referencing
3. Completed, ongoing or planned revisions to an existing linear referencing system
to meet new needs (especially, development of LRS to support enterprise
business practices).

Four detailed case studies served as the basis for much the field information collected in this
thesis. The selected agencies were:

1. Idaho Transportation Department (ITD)
2. Missouri Department of Transportation (MoDOT)
3. Pennsylvania Department of Transportation (PennDOT)
4. Washington State Department of Transportation (WSDOT).

2.8.2 Case Study Data Collection

Each case study involved initial phone interviews and collection of documentation followed by
two days of intensive on-site interviews. A representative from each agency helped to arrange
interviews with key personnel as well as providing documentation and editing assistance with the
final document. These efforts were central to the success of this thesis and reflect the wishes of
the participating transportation agencies to promote the further development of best business
practices in location referencing.

To help guide the on-site visits, a comprehensive questionnaire was drafted. A copy of the
questionnaire designed is provided in Appendix E. The questionnaire was designed using the
following considerations:

1. Desk-top knowledge of the key in-the-field issues faced by LRS practitioners
2. A one day workshops held on the topic of LRS (Lewis, 1994)
3. Review and input gained from field practitioners
4. Early interaction with some the agencies selected as candidates for possible
   analysis

The completed questionnaires were compared for both commonalities and differences.

It is interesting to note how the four studies may be ordered with respect to location referencing
program maturity. WSDOT’s system has been in place 50 years, Idaho’s for 20 years,
PennDOT’s for 10 years, while Missouri’s system is just now coming on line. The contrast
between these systems provides an excellent context for assessing some of the advantages and
shortcomings of the various techniques used for linear referencing.

2.9 Task 3: Expert Panels and Workshops

"I always have a consultant on tap, but never on top".
Winston Churchill.

It was felt that much of the existing LRS expertise resided with consultants. The purpose of these
task area was thus to formulate for LRS:
1. Gain field expert opinion
2. A fuller user needs expression
3. A common data modeling language. In the face of competing models, an attempt was made to facilitate the leading practitioners “speak the same LRS language”.

Expert panels and workshops were held on the topics of:

1. Transportation data models.
2. Transportation modal and temporal requirements
3. Object-oriented analysis frameworks and technology for transportation

This task area within the framing view of Rioch reflected “Practicism” as a worldview as a main purpose of the task was to gain a better understanding of “interpreted, contextually embedded meaning of data”. It covers both Human Centered, Cognitive Science and Systems heuristics as:

1. The cognition of the experts was an important factor in determining their requirements needs.
2. It involved gathering a more detailed appreciation of how more generally still different systems approaches view the LRS problem.
3. There was interpretation of system modeling languages

2.9.1 NCHRP Transportation Multi-Dimensional Expert Panel

The transportation modal workshop was carried out in November 1998 as part of NHCRP 20-27(3) activities. The comments here are the authors own. They may have no bearing on the published views of the Principal Investigators of that study. The final report of that study has not been published yet. This workshop was the larger, with an attempt to truly cover many of the modal interests in transportation, and with some variety of perspective even within mode. About 35 people attended. (NHCRP, 1998).

The NHCRP agreed to fund an extension of the 20-27(2) NHCRP project to review “Functional requirements For A Multimodal Multidimensional Location referencing System”. However, funding for this next stage was relatively limited, highlighting one of the problems of the field (perhaps the key ones). This project was awarded essentially as an extension to the team who had carried out the original NHCRP 20-27 work at the University of Wisconsin, with the implicit assumption of extending or amending the NHCRP 20-27(2) model.

Given the extensive field work carried out for other parts of the study here, it was not possible to carry out additional independent field work focusing more deeply on LRS functional requirements above that already carried out in connection with the DOT case studies. However, it was possible to collate comments earlier received and to be a participant in the NHCRP national research project, including attending the expert workshop and interacting with that project on technical matters.

The NHCRP 20-27(3) project was supposed to have formally completed and reported by this time, but has not at the time of writing. It is thus not therefore possible to comment formally on it. Indeed it is believed that the project has some way to go at this time and conclusions and recommendations to formulate and then pass through the Project Panel. It is believed that the project may finally complete as late as March 2001.
Towards meeting the goals of that project, a national technical workshop was held in Washington DC on December 3-5 1998 (a “Milwaukee II”). This meeting was a little more restricted being attended by a total 34 people (including the Project Panel and the research team). Participants at the previous 1994 Milwaukee meeting had included a greater number of systems and software developers and other national field experts. This meeting was originally aimed to be focused relatively more on the transportation practitioner community. As it occurred, only about 10 of the participants actually worked for state or local government transportation service supplying entities (e.g., state DOTs, MPO’s, etc.), or, a transportation service provider (e.g, transit agency, trucking company, etc). In fact, only three of the participants represented private sector transportation service companies. The difficulty again was noted of finding:

1. Private sector individuals willing to take time to donate to such topics as LRS
2. Public agency individuals who felt comfortable technically reviewing LRS.

Similar difficulties were found with setting up the panel for the LRS model compare and contrast workshop undertaken for this research.

Four “stakeholder groups” were created to assist with the identification of the functionality required by the different transportation user communities:

1. Transportation Planning, Highway Construction and Asset Management:
   This group primarily was intended to represent the data collectors, data managers and analysts who deal with lifecycle asset management at state DOT’s.

2. Highway Safety and Incident Management:
   This group was intended to represent those doing safety analysis at state DOT’s, police and emergency response services, and commercial trucking companies. This group both dealt with issues in real time (e.g., tactical emergency vehicle dispatch) and longer-term strategic (e.g., annual or multi-year safety analyses, typically done by state DOT’s).

3. Traffic Management and Highway Operations:
   This group was intended to represent those doing traffic management and operations. When the group considered their functional needs and reported it was found in practice that the needs of this area overlapped with that of the previous group, Highway Safety and Incident management, quite closely.

4. Transit Facilities and Operation; Commercial Vehicles and Fleet Management:
   This group represented both the public and private sector enterprises that move people and goods. While this group had differences (e.g, public versus private concerns), it had the communality of requiring or desiring more near real time network vehicle based information.

The research team was aware that these stakeholders groups do not cover the wider gambit of transportation. Other modal stakeholder groups that were not covered were for example:

1. Rail operations
2. Air
3. Waterways
Other groups not explicitly or directly covered were the ITS community (though traffic operations was) and military shipping. As worked out, as Groups 2 and 3 seem to have common needs issues, it is possible that with the benefit of hindsight, Groups 2 and 3 could have been amalgamated. Then a new group could have been created perhaps either from splitting Group 4 into transit and commercial vehicle operations, or adding a key area not covered, such as Rail.

Another possible issue with the stakeholder groups was how much they actually truly represented the interests of those groups. A list of those involved in the workgroups is shown in Appendix E.

As a participant in the workshop extensive notes were taken throughout. The author was a participant in Group 4. This group as it happened to include some of the “heavyweights” in the field, including names discussed elsewhere in this thesis, e.g., Fletcher, Vonderohe, and Spear, as well as representatives of bus companies and commercial truckers.

The stated overall purpose of the meeting and the work groups was to get the “stakeholder” groups to identify spatial/temporal operators that should be supported by a multimodal multidimensional LRS data model. A stated specific purpose of the process was to extend the existing NHCRP 20-27 model to cover multimodal multidimensional aspects. The NHCRP model is a Linear Reference model; however, the purpose of the latest NHCRP workshop was stated to be “multimodal multidimensional location referencing system data model. The term “multidimensional” implies general location rather than just a linear reference. The workshop did indeed consider 2D, 3D and 4D aspects and thus went beyond purely linear considerations. However, the effect of the significant broadening of scope was not directly addressed directly in the workshop. Throughout the workshop there seemed to be a fine tension between considering mostly linear aspects, and, also give a wider consideration to all multidimensional aspects. As research work for this thesis has indicated, the field of linear referencing is rich and detailed in any finer field consideration. Thus, by broadening the scope of the research so far, the research team may have a difficult time to grapple with the domain selected and report within the available time and budget (as in fact appears to be the case). The consideration given here, below, is mostly ID or LRS-based.

A formal public report of the NHCRP meeting and associated research is not yet completed.

2.9.2 Transportation LRS Data Modelers' Workshop

The transportation LRS data modelers’ workshop was organized by the author. Travel and other logistical facilitation including hosting by the USDOT Bureau of Transportation Statistics (BTS). It was held in March 1999. A subsequent public workshop was presented by the authors at the 1999 AASHTO GIS-T Symposium. (Lewis and Williams, 1999).

In terms of methodology, the expert panel workshops reflected:

1. A strong wish to gain practitioner level input
2. Use of “Delphi technique” type structuring of the transportation modal workshop
3. Use of facilitated interaction techniques for the LRS data model workshop.

These are described a little more fully in Chapter 8.
2.9.3  **Transportation OO Workshop**

In attempt to draw together some of the OO working experience in the transportation sector a one-day introductory discussion workshop on OO was prepared. It was presented at the Transportation Research Board on January 11, 1998 (Lewis and Petzold, 1998). It was attended by approximately 100 people. A basic tutorial was provided on OO concepts and technologies. This was drawn from the standard texts referred to in Chapter 3. Leading industry practitioners referred to some of their experience in modeling in non-transportation areas. Presenters included representatives from OGC, OMG, GIS vendors, the traditional transportation software modeling community and others interested in transportation information systems.

The preliminary work by the OMG to create transportation object standards (*CorbaTransport*) was reviewed, as well as some similar initial work by OGC. (These efforts are reviewed in Chapter 5, sections 9 and 10, of this thesis). The workshop included many of the main US spatial OO methodologists. No or very limited transportation OO or LRS actual field-work had been completed to date, so most of the interaction was at the introductory or conceptual level. It was not known ahead of time that this would actually be the case.

2.10  **Task 4: Practitioner Reflection and Use of Object Oriented Analysis Viewpoints**

The purpose of this task was, on the input of the previous four tasks, and a study of IT and Computer Science “best practices”, to investigate and suggest if and as feasible new designs for conceiving and implementing LRS solutions.

This task reflected Practicism, as a worldview as a main thrust of the task was to embed itself on contextual knowledge built up in the previous four tasks. However, as the work was also in large part based on empirical “neutralism” of best practices, the task could also be viewed as bringing together Practicism and Scientism.

The task largely reflects Software engineering heuristic. Appendix G reviews in more detail the activities that were carried out under this task.

2.11  **Chapter Summary and Conclusions**

LRS seems simple. In the first chapter, LRS was shown in fact to be relatively complex. In this chapter, it was seen that LRS can be viewed as a PIS or an EMIS. Research into how to research PIS is in its infancy. Research into how to research EMIS, is somewhat more advanced, but still seeking immature and seeking a wider research basis and epistemology.

2.11.1  **Progress Achieved**

The NCGIA (NCGIA, 1999) spatial research initiatives have considered research agendas for spatial information systems from 1990 to 1997. These initiatives appear to have given relatively

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4 The complexity of LRS will be further explored through the LRS Case Studies (Chapters 6) and Expert Panels (Chapters 7 and 8).
less focused consideration to the development of formal logical frameworks for carrying out research into spatial information systems.

Given the perceived multi-faceted “field nature” of LRS, attempt was therefore made in this chapter to create a research framework appropriate for this topic and to determine a basis relevant to “real in-field experience” of LRS. Five general guidelines for the research approach were adopted here. These were:

1. **Context Driven**: The research is an example of context driven research; the wider context of LRS is addressed.

2. **Practitioner**: In conjunction with the prior point, there is a strong concern with input of practical field experience and reflection on that, as proposed by Schon and others. (This is exemplified by use of case studies, expert panels, etc.).

3. **Multi-discipline**: A layered, multi-discipline approach, following the work of Reich. (“Best practice” disciplinary input from various fields and analysis points has been gained, including Computer Science, Geography, etc). The work of methodologists such as Reich and others also seems to have placed such “multi-perspective” research approach into a wider perspective and formal frame.

4. **Iterative**: An iterative approach, that is feedback was undertaken between the various work steps, where possible. Within this thesis a similar iterative process was used, even though the information is presented in this document linearly. For example, the presentation of case Studies in Chapters 6 and 7 required the fuller definition of terms provided in Chapter 4. However the fuller definition of LRS presented in Chapter 4 benefited from and directly drew from the work on Case Studies in Chapter 6. Hopefully, the reader and the research benefits from this iteration.

5. **“Reflection”**: As denoted in importance by Schon, an attempt to provide this is made at the end of each chapter and in the final chapter.

These themes are reflected in the specific work-steps that were adopted (using a “linear view of the research conducted here) or “tracks” using a more in parallel view of the work that was undertaken. In reality, the overall compromise approach was to take an iterative waterfall method. These research tracks are briefly summarized below in Table 8.

### Table 8 Research “Tracks”

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<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
</tr>
</thead>
<tbody>
<tr>
<td>TRACK</td>
<td>Epistemology</td>
<td>Semantics</td>
<td>Technology</td>
<td>Current Research</td>
<td>Modal Panel</td>
<td>Model Panel</td>
<td>Institutional Issues</td>
</tr>
<tr>
<td>PRINCIPAL PUR-POSE</td>
<td>Determine fields of relevance to LRS</td>
<td>Define the various network and LRS languages</td>
<td>Determine applications that may have significant impact on use &amp; setup of LRS</td>
<td>Identify all existing research; review LRS models</td>
<td>Gain expert opinion on LRS multidiimensional needs</td>
<td>Gain expert opinion on nature, strengths &amp; weakness of current models</td>
<td>Organizational needs and context for LRS</td>
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The research approach adopted is in effect a compromise between the linear step method and a set of parallel tracks. It is most closely associated with the iterative waterfall method described above.

The research methodology set-up here has thus been geared to the perceived existing nature and focus of the LRS topics. While set methods and formalized approaches have been proposed and put into place in some states, little of this has been based on more formalized research. In fact, after extensive investigation, it was found that no prior doctoral work has been completed on the LRS topic, and apart from the NHCRP 20-27 project reviewed here, very little if any more formal academic research.

The research methods here reflect “a practitioner’s approach”. While the approach laid out here is fairly elemental in its components, it would seem that there is a contribution here in grappling with research methodologies that develop a framework that includes but also goes beyond a sole reliance on case studies. Certainly, much use was gained from case studies. However, reliance on them alone would give a rather “in the trees” understanding of the field as a whole. Clearly further research here could expand, develop and test out such frameworks in more detail and their relevance to Planning Information Systems.

2.11.2 Ten Key Observations:

The ten main observations derived from this chapter were:

1. **Transportation Network Analysis**: This topic (in terms of traffic generation and flow algorithms) has been well-researched. This has been accompanied by the associated development of appropriate RM and techniques. Transportation network analysis, in terms of the description and analysis of transportation networks, (that is a description of the transportation infrastructure) has been less well described.

2. **Relevance**: The work in this thesis hits on a central theme identified by Schon of relative, “relevance or rigor” (Schon, 1987).

3. **Practitioner Topic**: LRS only has use and ultimate practicality in a “real-world” user context. The research approach adopted in this thesis needed to reflect this.

4. **Research Methods**: Planning or spatial information systems appear to have not yet had more attention given to research methodologies that are best associated with their execution. The better development of LRS may depend on the fuller development of RM’s appropriate in particular to practitioner-focused Planning and Spatial Information Systems research.

5. **Yoram Reich Work**: The work of Yoram Reich would appear particularly appropriate to develop for PIS contexts.

6. **LRS Foundational Research Base**: The fact that LRS had been little formally researched before, meant that a more “foundational” research work had to be completed here. Subsequent more focused research on individual topics that are identified from this thesis could use more focused tools. However, it is suggested
that the general framework briefly sketched here, may be of more general use in setting the frame of such research efforts.

7. **Iterative Waterfall Method**: This is the research approach most akin to that chosen here. It seems appropriate for PIS research.

8. **Multi-Faceted Review**: A number of different analysis viewpoints may be appropriate for a rich practitioner domain. To ensure relevance, multi-faceted topics such as LRS have research needs which need to rest on a multi-faceted, reflective, research approach (not just for example a set of four case studies alone). The four chosen here were in-depth literature review, case studies, expert panels, and a reflective practitioner exercise.

9. **Case Studies Reliance**: Reliance on case studies alone would appear too limiting for a topic such as LRS as well as other PIS topics.

10. **Research on RM**: Further work on LRS RM would mean that the limited available resources for such work is well spent.

2.11.3 **Main Conclusions**:

The danger of the research methodology adopted here, “topic-focused”, from a *methodological point of view*, it is to not go too deep on any one single sub-topic covered. The danger from a *practitioners viewpoint* of focusing on any one sub-topic (such as, for example, “the LRS data model”, or, “LRS institutional factors”), is that this particular field is still in the stage where fundamental issues need to be better laid out in a *holistic* fashion for realistic and meaningful assessment. Thus, as the more potentially field relevant, the more holistic approach was chosen for the current work.

Thus, the research here may be typified as “field-in”, rather than, what might in short be called, a “model-in” approach, which may be a classification of much of the work that has gone on in the 1990′s and to date. As will be seen in Chapter 5, there are a number of conflicting models of LRS, none of which have been first “driven up” or focused principally from a “*user needs driven perspective*".
2.12 Chapter References


3 Epistemology and Ontology for LRS

A priest sees people at their best, a lawyer at their worst, but a doctor sees them as they really are.

Proverb

3.1 Chapter Purpose

The Romans constructed a highway system that was of common form (as was described in Chapter 1). As was also briefly described in that Chapter, today we construct highways that are much more complex in their forms. Thus, the difficulty of directly applying the same simple rubric that the Romans did is more difficult to do.

Gaining common use of such rubrics requires adoption of a common epistemology, (which we defined in Chapter 2 as in short a general framework for organizing knowledge) and ontology (in short, a formal specification of the objects in that framework). In terms of the quote provided above, to best analyze any topic including LRS one needs to see “it as it really is”. “Seeing” is however conditioned by education (which provides framework), training (which provides language and lexicons) and current roles (which defines purposes).

The creation of a LRS is the creation of one form of “model of space”. Main tenets of this thesis to date are that:

1. There has been relatively little formal review work of LRS (this was especially so until the last 5 years)
2. What has existed has been mainly concerned with the constructing of formal LRS data models
3. Much of the construction of LRS models has gone on without a wider understanding of the wider context of LRS, including:
   a. The fuller nature of the transportation and spatial data issues posed by LRS
   b. Disciplines which may give useful analytical insight to the LRS issue
   c. Wider experience in data and process modeling
   d. Actual LRS field issues and experience.

This chapter attempts to provide a wider epistemological base for LRS. It does this though reviewing:

1. The nature of spatial and transportation data
2. Identifying and briefly describing the locational sciences (e.g., Geography, Civil Engineering) of relevance to LRS, and briefly commenting on them and key literature
3. Reviewing the other science and disciplines of relevance to LRS (e.g., Information Systems and GIS).
4. Analyzing the nature of data modeling, the constraints on modeling and Systems Analysis.
Within the framework of this current work, only relatively brief summary and critique can be provided. Reference is provided to the key external work. The following Chapters 4 and 5 go onto more fully review LRS field experience in detail based on case study experience.

3.2 The Nature of Spatial Data

This section briefly reviews some of the characteristics, nature and uses of spatial data. It is appropriate to review some of the general characteristics of spatial data before considering the disciplines that have a heavy focus on using spatial or locational data. Spatial data can be defined in several ways. Principal means are:

I. A "GIS definition": The coordinate or other location data which define location in space, or
II. An "Operational definition": Any data that has location as a primary means of reference.

The first definition is a "GIS definition", because it separates the spatial data from the attribute data (ESRI, 1992). The second definition bundles coordinate data with information that was collected with that coordinate (or, was later added). Thus, an accident on a highway could be defined as "spatial data" if it has been collected within spatial data collection exercise and stored and retrieved through a spatial data management and display system.

Dahlberg (1985) describes in a little more detail the characteristics of spatial data to include the following ten aspects:

1. Coordinate accuracy
2. Coordinate system
3. Map projection
4. Geometric form (point sets, networks or flows, patches or cells, surfaces or volumes)
5. Level of measurement (nominal, ordinal, interval, ratio)
6. Cartographic encoding model (pairing of geometric form and level of measurement)
7. Spatial resolution at data capture
8. Spatial generalization
9. Classification
10. Data quality (evaluation of data in relation to map specifications and cartographic data standards).

Spatial data quality may be of overall and particular concern for any application. Five general characteristics are held to generally describe the quality of spatial data. These are:

1. Lineage (is it known?)
2. Positional accuracy (both absolute and relative?)
3. Attribute accuracy (the degree of correctness?)
4. Logical consistency (for example, do parts on one network interconnect?)
5. Completeness (what percentage of total data is missing?)

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Walter (1987) reviews some of the generic causes of error with transportation data as a whole. Dahlberg (1986) considers spatial data and describes the issues of combining spatial data from different sources. He pointed to some possible options for developing solutions. For example, it is interesting to note that 15 years later in a similar paper, Byrom and Pascoe (2000) record that many of the same problems exist in processing data from different sources. They suggest that misuse of spatial data from different sources can be restricted by either:

1. Restraining certain operations on datasets
2. Analyzing the metadata of the datasets to decide their sustainability for use in various applications

This thesis takes the view that what exactly is spatial data has been relatively poorly defined and understood in detail. For example, does spatial data implicitly include the metadata that describes characteristics of its collection, accuracy, etc?

Samet states that spatial data “consists of points, lines, rectangles, regions, surfaces, and volumes” (Samet, 1990a). He then produces two detailed volumes on spatial data infrastructures without really considering what are the inherent characteristics of spatial data.

Spatial data may be stored in spatial data architectures or infrastructures. By utilizing one GIS vendor’s product implicitly one is “buying into” the GIS architecture of that vendor. The Open GIS Consortium (OGC) is attempting to put in place a generic GIS architecture. Federal agencies are attempting to put in place a national spatial data infrastructure (NSDI) though a coordination committee of various federal agencies that utilize spatial data.

3.2.1 “Messy Problems”

It will be argued and demonstrated in more depth throughout the course of this thesis that in short spatial data:

1. Is of varied quality
2. Has inherent uncertainty associated with it
3. Exceptions rather than being the exception are the quite common matter with spatial data.

LRS is in a wider context is an example or surrogate for the class of problems Schon calls “the messy class” (Schon, 1982). Evans and Ferreira (1995) in considering the research needs of a messy world with messy technology define “messy” as, “imperfect and dynamic”. LRS is a messy problem for a number of reasons. These can include for example:

1. Networks are defined in different ways by different user groups.
2. Definition of location on a network can be ambiguous using different or even one singular metric.
3. Spatial data are implicitly inaccurate and prone to uncertainty.
4. Language used in connection with networks and space is ambiguous.

Many topics in the spatial domain provide examples of messy problems. For example:

1. Snapping points to lines
2. Merging multiple representations of road centerlines
3. Conflating (or integrating) networks
4. Network “generalization”.

These problems typically look easy but in fact are complex. They do not always have one “right” answer but often involve questions of human judgment and interpretation that may differ in steps and exact results even between skilled analysts. “Messy problems” are not always directly approachable by a simple linear exploration process or analyzable from singular analytical viewpoint or mathematical approach.

The National Consortium for GIS (NCGIA) has been instrumental in researching issues of spatial data uncertainty and appropriate representation in recent years. (Baird, et al, 1999)

3.3 Nature of Transportation Spatial Data

Transportation data supports transportation planning, design and operations. There has been a renewed interest in the last three to four years on the importance of transportation data considerations. Alan Pisarski in his paper as distinguished lecturer to the 1999 Transportation Research Board (TRB) noted three historical phases in transportation data, policy and planning (Pisarski, 1999):

1. “Census Transportation Era”: 1962-1977. This era was characterized by the adoption of Census transportation data for modeling purposes. Conflicts occurred over this activity and regulatory data collection.
2. “Night of the Long Knives”. 1977-1990. There was a disinterest in data and analysis. There was a shift to the economic census and a shift form planning facilities to managing what existed.

The recent TRB Record with which Pisarski’s paper is part has twenty over papers concerned with improving the quality of transportation data (Pisarski, 1999), which indicates a growing awareness of the importance of such issues.

3.3.1 Use of Lines to Represent Network Components

With LRS, we are typically dealing with place and passage on “lines” that represent transportation features. A collection of lines has already been defined as a network. This simplification has benefits and costs.

Often straight lines (or sets of straight lines) are used on many simplified maps (such as in subway maps prepared for many cities) to represent traversals between two points (when in reality the traversal may be much more curvilinear). The reason for this is that the straight line (or a line which if not straight, has been reduced to some simplifies form) may convey the appropriate amount of information for the application at hand. As Tufte, one of the leading commentators on graphical expression notes in this context, “it may allow viewers to edit and focus directly on the relevant – compensating somewhat for loss of context”. (Tufte, 1990). Lines may have “just enough information”. The show the vital connectivity between two points, which
may be the critical information to determine the possibility of connection and thus passage between two points.

A line is all one needs to know “sufficiently well” where one is on a subway system. It is typically also all a DOT manager needs to know for the purposes of such activities as pavement management or snow-plough routing. This topic will be returned to in Chapter 9.

3.4 Flexibility in Transportation Design Activities

As noted in Chapter 1, Transportation is essentially concerned with the design and analysis of networks. Transportation data shares many of the characteristics of spatial data. We wish to categorize and make generalizations about transportation spatial data. How transportation data can be so varied, “on the ground”, in the field is exemplified by taking the case of highway design – the actual design and physical construction of the highway or transportation facility. An important concept in highway design taught to designers is that every project is unique. While standards for highways design are quite well set (for example, each state has a Highway Design Manual, or, HDM), FHWA guidance indicates that in designing highways there are unique factors that designers must consider with each highway project. These include as partial examples:

1. The setting and character of the area
2. The values of the local community
3. The needs of the highway users, and
4. The challenges and opportunities whether the design to be developed is for example for a modest safety improvement, or, for example, 10 miles of new-location rural freeway, there are no patented solutions.

For each potential project, designers are faced with the task of balancing the need for the highway improvement with the need to safely integrate the design into the surrounding natural and human environments.

The FHWA Flexibility in Highway Design Guide illustrates the flexibility already available to designers within adopted State standards. These standards, often based on the AASHTO “Green Book”, allow designers to tailor their designs to the particular situations encountered in each highway project. Often, these standards alone provide enough flexibility to achieve a harmonious design that both meets the objectives of the project and is sensitive to the surrounding environment.

Flexibility on the design of objects requires additional flexibility required in the data models required to formalize, as will be touched upon in a later section of this chapter (see Section 3.6). As was noted above, with linear referencing systems with our typically concerned with highway management activities and the interpretation of highway data at a planning level of analysis rather than design. However, the fact that there is flexibility in highway design activities provides a situation where planning level representations need to be able to reflect the diversity of highway design forms that occur.

The following section reviews the various disciplines that have concerned themselves with analyzing networks and in particular transportation networks.
3.5 Locational Analysis and Sciences

How do we as practitioners or researchers perceive and analyze transportation spatial data? What are the disciplines provide fuller analytical:

1. Perspective
2. Framework
3. Method and tools, and
4. Language?

Adoption of any one discipline will frame the tools and the language one uses in analyzing networks. Such disciplines may be broadly divided a number of ways. A two-category division is:

1. The "locational sciences" (e.g., Cartography, Geography, etc.)
2. The "informational and analytical sciences" (e.g., Information Systems or Computer Science, Mathematics, Systems Analysis, etc.).

In reality, the division is somewhat arbitrary and most disciplines inter-merge. For example, GIS as a discipline arguably sits across these two disciplinary sets.

The key disciplines of relevance are reviewed below. In reviewing them a brief attempt is made to briefly summarize the field and its potential relevance to the wider and fuller appreciation of LRS.

3.5.1 Mathematics

Mathematics, the reduction of relationships to numerical or symbolic form, fundamentally underlies much of the locational and computer sciences listed above. Various in fact mathematical routines may be used for example to snap points to lines, carry out various averaging measures of survey data, calibrate route lengths and other spatial data averaging and processing tasks.

Mathematics has two main branches, algebra and geometry. Geometry is of concerned with space, and in that sense is “locational” (the “locational” of this section being very much an applied sense of the term). A branch of geometrical mathematics, topology, is concerned with the connectedness, enclosure, adjacency and certain other properties of objects that may not change when the geometry of objects change. Topology actually remerges algebra with geometry. Topology is key to the consideration of transportation networks. Topology can describe networks. Topological measures may give metrics of, for example:

1. The “covering nature”
2. “Connectedness”
3. “Compactedness”
4. Density, and
5. Other characteristics of networks.
Topology has its own language of networks (a language which is in part shared with geometry). For example:

1. **Edge**: Arc or line joining two points
2. **Vertex (vertices)**: Where edges meet
3. **Odd vertex**: Where an odd number of lines meet
4. **Even vertex**: Where an even number of lines meet
5. **Tree**: A network that is all one piece, in which every line terminates in an otherwise free vertex

There are many reference books on topology and branches so it. (see, for example, Hicking and Young, 1988, Barr, 1989, and Gemignani, 1972). Topology provides a rigorous basis for the analysis of network characteristics and network problems. *Graph Theory* is the oldest and most geometric branch of topology. *Graph Theory* has its own established field (e.g., literature, journals and conferences). Trudeau (1976) provides a more elementary text covering the basics of the field, Chartrand (1977) slightly more advanced.

The original (this problem led to the genesis of the field) and most famous problem for graph theory was the “Koenigsberg bridge.” This problem was defined by seven bridges connecting two islands; the problem was to walk a complete a walk circuit, but cross all of seven bridges only once. Euler solved the problem by creating a proof that to traverse the edges only once there could only be an even number of odd vertices in the network. Other topological theorems may help analyze other network situations.

In terms of work of possible more immediate and direct relevance to LRS, Ophiem (1982) provided an algorithm for fast data reduction of lines. Bryant (1967) looked at graph theory applied to electrical networks. However, interaction with leading graph theoreticians and leading graph theory texts turned up surprisingly little additional material on network characterization or other topics that might be of more direct help with the consideration of transportation network representation and LRS.

### 3.5.2 Computer Science, Information Science, and Management Information Systems

*Computer Science* is the study of computers, including their design (architecture) and their uses for computations, data processing, and systems control (Encyclopaedia Britannica, 2000). As an independent discipline it dates about 1960. It is based on the two core disciplines of mathematics and electrical engineering.

*Information Science* is the discipline that deals with “the processes of storing and transferring information” (Encyclopaedia Britannica, 2000). The term “Information Systems” (IS) includes the traditional concept of a “Database System” but extends beyond to incorporate other technologies relating to the distribution and access of data. Components of IS include natural language processing, expert systems, graphic representation, and distributed systems development.

The institutionalization of information science has been stalled by the appropriation of many parts of it by other disciplines (e.g., Computer Sciences, Engineering, etc).
A LRS may be thought of as a Management Information Systems (MIS). It may even be thought of as an EIS (Enterprise Information systems) as the data in it may be fundamental to a number of agency-wide management information systems.

GIS is a fruit of amalgamating Geography and Computer Science. Expert Systems (E.S.) was an area for the integration of Planning and Information Systems in the early 1990’s. (Kim Wiggins, et al, 1990). Despite much fanfare, and potential promise, further development of this area has tended to involve the construction of not “expert systems”, but the use of A.I. concepts in the design and coding of mainstream data management systems and associated decision support systems.

3.5.3 Cartography

Cartography is “the art and science of graphically representing a geographical area, usually on a flat surface such as map or chart; it may involve the superimposition of political, cultural or other non-geographical divisions onto representations of a geographical area” (Encyclopaedia Britannica, 2000).

It grew out of the early quest to depict hunting and fishing grounds. Map projections are used to deal with the issue that the world is a globe (or “geod”). Map projections retain as accurate at least one of the following dimensions, but must distort at least one: bearing (angle), distance, area or scale.

Cartography and geography are closely associated; many cartographers are geographers and vice-versa.

A review of traditional mapping texts (see, for example, Greenhood, 1975) in chapters on coordinate systems, rarely consider the one-dimensional (linear) case. The one-dimensional case has thus had less formal academic review to date. The cartographers Douglas, D.H. and T.K. Peuker (1973) review methods of network characterization.

3.5.3.1 Cartographic Issues

Cartographers are concerned both with the accuracy of spatial data and also map user “digestability”.

More accurate networks have larger scale, are typically more recent and have had further cartographic and surveying checks. A distinction is made between accuracy and precision. The internal representation of data in a GIS may be “very precise” (say, “12 digits of precision”), but the data itself may not be very accurate. Scale is the measurement of distance on the ground and on a map. 1:100,000 is larger than 1:1,000,000. A map has scale, a spatial database does not (That is, only the metadata stored with a set of coordinated within the computer database will know the scale that the data was input at –scale being determined essentially by the operation by which the data was collected, or, subsequently corrected to).

Map scale thus has implications for accuracy; Table 9 shows the relationship among geographic extent, typical activities and the scale and precision of spatial data. Resolution data (available here in metric) is the minimum distance over which change can be recorded at a given scale. There is increasing generalization at smaller map scales.
Table 9  Map Scale, Accuracy and Uses

<table>
<thead>
<tr>
<th>Geographic Extent</th>
<th>Type of Activities</th>
<th>Scale of Spatial Databases</th>
<th>Precision of Spatial Databases (ft)</th>
<th>Resolution</th>
</tr>
</thead>
<tbody>
<tr>
<td>State</td>
<td>Statewide Planning and Management</td>
<td>1: 500,000</td>
<td>830</td>
<td></td>
</tr>
<tr>
<td>Multi-District</td>
<td>Corridor Selection</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>District</td>
<td>District Planning</td>
<td>1: 100,000</td>
<td>170</td>
<td>50m</td>
</tr>
<tr>
<td>District and Metro Area</td>
<td>Facilities Management</td>
<td>1: 12,000 -- 1: 24,000</td>
<td>30 - 40</td>
<td>7- 12m</td>
</tr>
<tr>
<td>Metro Area</td>
<td>Corridor Analysis</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project</td>
<td>Engineering Design</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Project</td>
<td>Construction</td>
<td>1: 120 – 1: 1200</td>
<td>0.33 - 3.0</td>
<td>- 6.25cm</td>
</tr>
</tbody>
</table>

1: 24,000 scale data is a common standard for many mapping applications, including for state DOT’s and relatively cheap data sources at this scale are available. 1:12,000 scale is a scale used in DOT’s for smaller states (e.g., Delaware). Going to 1:1,200 scale data, there is a massive increase in data storage. Many COTS GIS’s are generally relatively less well-adapted to fully and best deal with engineering level data.

Figure 8 gives a brief indication of levels of transportation network representation at different scales.

In terms of the availability of cartographic datasets other key questions include:

1. What is the age of the dataset?
2. When was it last updated?
3. How often will it be updated?
4. Who will be responsible for updates?

For reasons of maintaining cartographic integrity and the value in existing datasets, cartographers may often prefer to update old, rather than replace entirely with new.
Figure 8 Levels of Network Representation

1:100,000

Railroad

1:24,000

Bridge

Stream

Crossing

Street

1:2,400

Tracks
3.5.3.2 Cartographic Linear Products: Straight Line Diagrams

There are many types of cartographic product.

One of Cartography's key historical contributions to transportation and LRS has been the production of Straight Line Diagrams (SLD's). In these, the presence of features on the road is mapped on a straight line representation of the road. Thus, an SLD is a one-dimensional presentation of a roadway and the features that compose it. At least one state has published electronically its SLD's (New Jersey DOT, 1997). An example is shown in Figure 9. (Note: the file format translations used have not left here a crisp image).

SLD's or 'strip maps', are the central component of many document-oriented LRM's, and generally avoid the costs of installing and maintaining signs in the field. While manually produced in many DOT's for many years, these are more typically these days computer-generated. They typically use:

1. Primitive symbology
2. May include diagrams of the roadway path
3. Together with symbols and annotation, describe key intersections, distances and infrastructure points.

SLDs may be loaded on laptop computers within data logging vans to aid direct input of infrastructure features into the system. Information from all roving data collection assets are then consolidated into a central location and merged with existing linearly referenced data.

SLD's map the presence of features on the road on a straight-line representation of the road. In such SLD's, it can be seen that (transportation) features have true length (x), but not true position (x,y).

The use of SLD's has been fairly well established in many state DOT's for a number of years. Many state DOT's have maintained SLD books, and now may be moving to electronic versions. The SLD provides the key information necessary for many highway maintenance purposes in what turns out for many is an adequate format. Some would view SLD's as an older methodology or technology. However, a recent NHCRP report (NHCRP Report 437, 2000) seems to further promote the use of SLD's. Their production may be facilitated by the use of automated data collection techniques (such as GPS equipped data collection vans) and automated software that can be used to produce SLD's.
ROUTE NUMBER (Direction By Description)  Route Mile Post Limits for This Sheet

Symbol Legend:

Features
Federal Aid Interstate Route
U.S. Numbered Route
New Jersey Posted State Highways
County Roads
Interchange Number
Grade separated interchange (full or partial)
Traffic Monitoring Site (WIM, AVC, or VOL)
Toll Plaza
Undivided Highway with Jug Handles and Traffic Signal
Divided Highway with Median cut with and without Jug Handle
Dualized Highway (Express and Local)

Structures
Road Overpass
Road Underpass
Pedestrian Overpass
Pedestrian Underpass
Cattle Overpass
Cattle Underpass
Structures under 5 000 (��)
Structures 200 and Over (①)

Structures

KILOMETERS Scale: Indicates authority responsible for mainline roadway.
Jurisdiction Functional Class: Classification of road according to the character of service provided. Approved by FHWA in 1992.
Federal Aid System: Federal funding eligibility program.
Control Section: On number codes for internal NJDOT accounting purposes.
Speed LIMIT: Recent speed limit of roadway.
Number of Lanes: Indicates the total number of traffic lanes in BOTH directions.
SB/WB Shoal: A physical description of each section of road. The limits of each feature are located perpendicular to the centerline of that roadway.
SB/WB Pavement: A physical description of each section of road. The limits of each feature are located perpendicular to the centerline of that roadway.
Med. Type: A physical description of each section of road. The limits of each feature are located perpendicular to the centerline of that roadway.
Med. Width: A physical description of each section of road. The limits of each feature are located perpendicular to the centerline of that roadway.
N/S/E/B Pave: A physical description of each section of road. The limits of each feature are located perpendicular to the centerline of that roadway.
Traffic Volume: Traffic volume estimate of the AADT (Year Counted).
Traffic Sta.: Internal NJDOT traffic monitoring system identification number.
HPMS Sample Site: Highway Performance Monitoring System - These are sample sections where detailed geometric, operational, and condition data are collected.
Structure No.: Unique structure identification number, if available.
Contract No. & Date: Shows route section number, and opening date for initial construction, major reconstruction, and last resurfacing (route number changes, if any).

Figure 9 Straight Line Diagram

S.R.I. # (Standard Route Identifier)
3.5.4 Geography

Geography is the study of the surface of the earth. It is one of the oldest subjects of study and it has been called the mother of sciences. “Geographic study is particularly concerned with location, with areal patterns, with interrelationships of phenomena (especially of the relationship between human society and the land...)” (Encyclopaedia Britannica, 2000). Geography has historically been most focused on descriptive analysis and inquiry.

In some seminal sense, such formal academic geographic spatial inquiry reached a peak around the 1950's and 1960's with the work of Christaller, Haggett, Losch, Morrill, B.L.J. Berry and others. Many mathematical models were created to analyze spatial hierarchy, the location of central places and spatial interaction patterns. These formal models, consisted of, “axioms expressed in formal language together with mathematic rules to infer conclusions from these axioms” (Mark and Frank, 1996). Many of the seminal works in the field were published in this period, covering for example the use of gravity models, central place models, spatial diffusion models, etc. Probably the most comprehensive work in collating that body of knowledge and work is that of Abler, Adams and Gould, “Spatial Organization”. Thisse (1996), noting that the field of location theory has been somewhat marginalized, provides a compendium of many of the key papers in location theory, many going back to the 1950's.

The “hey-day” of fresh thinking of spatial analysis in Geography was around the 1960's -- before many of the models that were produced could be readily or cost-effectively tested on a larger scale on computer-based systems. A key paper in terms of network characterization was that of Pitts (1965).

In the 1970's and early 1980's, Geography as an academic discipline, had lost some of its popularism, at least in North America. It regained its standing to some degree through the advent of computer-based systems, in particular Geographic Information Systems (GIS) and areal mapping by satellites.

Geography offers to LRS a wider contextual and analytical framework covering spatial data. The fascination that geography had in the 1960's for land use and locational models was often stymied by the lack of spatial data. However, reference to the literature above indicate that this left room for desk-top contemplation and review. It seems that some of the depth and quality of analysis that was done then has not been fully repeated since.

Regardless of the dimension, do now many analysts often “spatially compute” -- before they fully “spatially think”?

3.5.5 Urban and Regional Planning

Planning is defined as the, “the programs pursued in most industrialized countries in an attempt to achieve certain social and economic objectives, in particular to shape and improve the urban environment in which increasing proportions of the world’s populations spend their lives. Evidence of urban planning – such as orderly street systems ....”. (Encyclopedia Britannica, 2000).

“Urban Planning is a multi-dimensional and multi-disciplinary activity embracing social, economic, political and technical factors. Solutions to urban problems frequently require not only
numerical analysis but also heuristics analysis, which in most cases depend on the planner's intuitive judgment. Conventional quantitative techniques, that deal mainly with numerical analysis, lack the capability of incorporating the heuristic knowledge of planners into problem solving". (Kim, Wiggins, et al, 1990).

Planning at it's core also has for many of its concerns been vitally focused on location, as many planning decisions are locational decisions. For example, one of the chief planning concepts of the twentieth century is zoning — which requires an accurate maps and consideration of locational analysis.

"Planning seeks to regulate or control the activity of individuals and groups in such a way as to minimize the bad effects which may arise, and to promote better 'performance' of the physical environment in accordance with a set of broad aims and more specific objectives set out in a plan .... It must be extended to encompass the whole fabric of spatial relations between activities and complexities of their interactions" (Mcloughlin, 1970, p.59)

Urban and Regional Planning has historically as a discipline perhaps not been quite so exclusively concerned as Geography to descriptively “model space”. The advent of modern spatial information data collection (e.g., GPS, satellite imagery, etc.) and storage technologies (e.g., Geographic Information Systems) has made this possible. Compared to the restraints that the 1960’s geographers faced, adequate computer power is available today at very reasonable cost to run even the most complex planning models. GIS are being increasingly used by Planning agencies at least to inventory their spatial data. The wider in field or academic drive to model or understand relationships between “everything in geographic space” seems at least from the published literature (books and published papers) to be relatively less than it was than in the 1960’s. This change may in part reflect:

1. The relative difficulty in meaningfully further extending at the conceptual level some of the models. (For example, you cannot so readily today get a PhD just by applying a gravity model to a set of socio-economic data; that has been long done).
2. Changes in wider academic predilections, which can occur for a variety of reasons. As noted below, new academic foci have appeared.
3. The field has a whole has put much practical and intellectual energy into gathering and organizing spatial data in the last decade and the relative synthesis and analysis of this field has been less.

An approach that reflects an awareness of system analysis, but with a more measured and considered use of models, is reflected in more recent books (see for example, Wyatt, 1989). In fact, many of the more recent works focus on identity and location being phenomena that are cultural and psychological in perspective. Men and women see space differently, men preferring maps, women directions. Social and symbolic geography are seen as vital determinants of "sensing space" (Carter, et al, 1997). Certainly, many spatial analysis models are produced and used. Figure 10 below shows the planning models as exampled in use in the State of Utah.
Many of the texts on GIS are more concerned with the discipline and structure of GIS data models, rather than of the spatial nature of the phenomena and models that have been used to describe them. While this is understandable, lack of full appreciation of the richness of spatial occurrence is at the root of why “GIS is difficult in the field”. Eighty percent of GIS-T projects, for example in the transportation domain, go over their budget (Lewis, 1999). For example, one of the more complete works in the field, the 700-page tome, *Fundamentals of Spatial Information Systems*, (Laurini and Thompson, 1992), takes about 20 pages (but, only 20 pages) to review the nature of spatial phenomena, spatial modeling needs, and the main spatial models, etc. The review is thus both relatively very high-level and very limited.

There are some more recent wide-ranging initiatives in this area of note, often undertaken in a transportation context. For example, Miller et al (1998) attempt to define a framework for enhancing integrated transportation land-use models. Their key work focuses on “the representation of land-use transit interactions, so that these models can provide useful, credible and timely inputs into the transportation/transit planning process”.

Certainly, those who seek to analyze and utilize modern computer-based spatial analysis techniques would do well to revisit some of the seminal work in spatial analysis and modeling completed in and around the 1960’s. There is a need to better integrate the wider literature on spatial modeling with the requirements of spatial information systems.5

5 The author is not aware of a modern text that attempts to draw together the wider history and coverage of spatial modeling and spatial information systems in a more complete and more structured manner. An example of the juxtaposition of the two Is at the heart of this thesis.
Compared to normative geography, Planning as a professional profession has been more concerned with *proscriptive* types of analysis. The prospective contribution of urban planning to LRS is in helping formulate the proscriptive uses to which LRS data may be potentially put.

### 3.5.6 Civil Engineering

It is “the profession of designing and executing structural works that serve the general public”. (Encyclopaedia Britannica, 2000).

The term ‘civil’ is used to differentiate from “military” engineering. While the Roman military were often responsible for urban planning and highway construction, the formation of the “Ecole Nationale des Ponts et Chaussees” in Paris in 1747 gave birth to the modern field of Civil Engineering. Transportation Engineering is branch of Civil Engineering. “Transportation” (US) or “Transport” (UK) as a graduate degree can cover either Transportation Planning and Transportation Engineering, or both. This thesis is concerned with transportation analysis (largely in a transportation planning context).

Roads need to be physically designed and developed. They represent a rich set of feature types, as was already briefly demonstrated earlier in Table 1 and described in Section 3.4.

A potential principal contribution of Civil Engineering is that by understanding the nature and possibilities of the Highway Engineering design permit the larger set of feature types that can be placed in LRS to be identified, upfront.

### 3.5.7 Surveying

Surveying as a profession is “a means of making relatively large-scale, accurate measurements of the earth’s surfaces. It includes the determination of the measurement data, the reduction, and interpretation of the data to useable form, and, conversely, the establishment of relative position and size according to given measurement requirements. Thus surveying has two similar but opposite functions: (1) the determination of existing relative horizontal and vertical position, such that used for the process of mapping, and, (2) the establishment of marks to control construction or to indicate land boundaries”. (Encyclopedia Britannica, 2000).

A potential key contribution of Surveying to LRS is a better appreciation of spatial accuracy issues particularly in coordinate data collection.

A concern referred to in this thesis is how to use improved survey grade quality data such as being generated through the use of GPS. However, the main concern here is with the set-up and use of LRS, which be viewed as principally viewed in first order as a planning level activity.

### 3.5.8 Transportation

This section briefly reviews transportation information communities, transportation networks, current transportation agency institutional issues and a particular focus of transportation currently, ITS, Intelligent transportation Systems.
3.5.8.1 Focus of Transportation Organizations

Transportation as a professional focus has also changed in recent years. The role of the transportation agency has in particular changed significantly in the last two decades. Gone are the days of highway construction on a grand scale and continual expansion of the transportation system. Social and environmental concerns have become an integral part of transportation planning, resulting in the current trend of making the best use of the existing system rather than simply building more roads. At the same time, the technological revolution has provided a profusion of tools for collecting, managing and analyzing information of all kinds.

Transportation agencies are under increasing pressure to apply their information resources with increasing sophistication to decide where the best investments are to be made in the transportation system (AASHTO IS Committee, 1998). However, transportation agencies have traditionally managed their data as a classic set of “data islands” or “stove-pipe” applications. The vast majority of data held in state DOTs is still held this way. (See Figure 11).

To access data in a provincial or state DOT, it is necessary to know how exactly to access it. If the integration of different datasets is required, it is necessary to have an index or key to do so. For example, we may reference bridges, potholes or accidents principally by where they occur on the road network.

Figure 11 Transportation Agency Data Islands

![Diagram of Data Islands, Application Islands, and GIS Systems]

Comprehensive reviews of the data held in state DOT’s such as Pennsylvania Department of Transportation (PennDOT) and the Wisconsin Department of Transportation (WisDOT) have indicated that approximately 70% of the data has location as a primary or key reference (source). Most transportation investments are made at some location along a roadway or other linear feature. The key to integrating and analyzing these data is where they are located. Location is the key to integrating transportation data, and thus to making many decisions about transportation investments. Location is thus a natural key by which to integrate transportation data.
In Figure 12, it can be seen that in a typical transportation agency there is a set of data acquisition, assemblage and maintenance processes. These occur between "the reality" of the transportation world (that is the universe of transportation related objects), and, the end-user. The end-user in a transportation context might be various levels of decision-maker within the transportation agency or transportation external users. Increasingly the role of external data users is of greater importance in transportation agencies. State DOT's have often become the prime maker of public agency maps within a state (for other state departments, presentations by the Governor, highway maps, etc.) and also provide key presentational products to the public planning review process. No single data acquisition processes are specifically shown in the diagram, but such activities occur in state DOT's through the use for example of videolog vans, the collection of highway geometric design data, or, other field data collection activities. While the size of DOT databases had grown about 5% a year in the 1980's, with new data collection activities in the 1990's, including in aerial photogrammetry, use of satellite data, laser swath mapping and videolog vans, some DOT's were doubling the size of the databases in 2 or 3 years. (reference, Wisconsin DOT IT Plan)

Examples of the particular types of data the transportation agency collects are shown in the fifth ring from the center in Figure 13, e.g., traffic flow data, video-log data, accident, etc. (Some of the terms used in the diagram are defined in the Abbreviations section at the beginning of this thesis, for example DEM is Digital Elevation Model). Data that is held in individual data areas then may be "fused" or merged to produce composite report.
An important DOT data integration example is for the activity of safety analysis, and in particular accident reconstruction. In this activity, typically design or highway geometric files, traffic flow data, prior accident files, and other safety related data, etc., are all analyzed and merged in conjunction with each other. The data fusion process may be standardized for key areas of activity, such as for safety management, to produce a “safety management system”. For the last 40 years of computer use (a mainframe was first introduced in a DOT in Wisconsin DOT in 1959), results of such analysis were often “mounds of green computer print out”. In the last decade or so, increasingly visualization tools (graphs, maps, etc.) have been produced to aid user interpretation.

Decisions about where to make investments are based on data about the transportation network (road, rail, etc.). The key to integrating these transportation data is where on the transportation network they are located, where traffic is congested, where accident rates are high, where growth is expected to occur. Location is the key to integrating and analyzing transportation data, and thus to making decisions about transportation investments. LRS is the data integrator (see Figure 14).
With the context of this thesis, Transportation as an academic profession has largely focused on the analysis of flows on networks. There is a rich formal literature on this topic. (See, Newell, 1980, Sheffi, 1985, Thomas, 1991, Sussman, 2000).

3.5.8.2 The Transportation Information Communities

Transportation is an activity fundamental to human behavior. Transportation is essentially concerned with the movement of goods and people from one location to another. It is an activity that touches upon many wider aspects of human life and conditions. Many economic, social, environmental, and other aspects of life are vitally affected by transportation. Transportation typically consumes about 20% of GDP in developed countries.

Transportation is made up of a number of modal communities. Transportation is divided functionally, administratively, and commercially across transportation modal areas such as road, air, rail, and waterways, as shown in Figure 15.
Other transportation communities or “groupings” exist – for example, those that deal with public transit, freight, intelligent transportation systems, etc. These groupings in part may be seen as reflecting divisions along standard enterprise information architecture analysis lines, as shown below. These different modal groups are one of the many information views of transportation (see Table 10).

<table>
<thead>
<tr>
<th>DATA</th>
<th>BUSINESS PROCESS</th>
</tr>
</thead>
<tbody>
<tr>
<td>• IS Managers</td>
<td></td>
</tr>
<tr>
<td>• State DOT LRMs</td>
<td></td>
</tr>
<tr>
<td>• USDOT Bureau of Transportation Statistics (BTS)</td>
<td></td>
</tr>
<tr>
<td>• Association of American Railroads</td>
<td></td>
</tr>
<tr>
<td>• HEEP (Highway Engineering Exchange Program)</td>
<td></td>
</tr>
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</table>

<table>
<thead>
<tr>
<th>ORGANIZATION</th>
<th>TECHNOLOGY</th>
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</thead>
<tbody>
<tr>
<td>• CEO'S, CIO'S</td>
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</tr>
<tr>
<td>• Transportation Research Board (TRB), Inst of Transport Engrs (ITE)</td>
<td></td>
</tr>
<tr>
<td>• AASHTO</td>
<td></td>
</tr>
<tr>
<td>• US DOT, state DOTs, etc.</td>
<td></td>
</tr>
<tr>
<td>• Intelligent Transportation Systems</td>
<td></td>
</tr>
<tr>
<td>• Association of Vehicle Manufacturers</td>
<td></td>
</tr>
</tbody>
</table>

Table 10 Transportation “Information Views” I

In Chapter 9, within a consideration of institutional issues, a framework (the Zachman framework) that attempts to integrate all of the above elements is laid out.

The 1991 Intermodal Surface Transportation and Efficiency Act (ISTEA) called for the inter-operating and management of transportation modes. “Next-T” legislation (TEAC 21) carried forward some of the general aims of this original ISTEA legislation, but put more focus on local agency activities compared to federal. There is not now funding or support for federal LRS development, standards, etc.

Information barriers have hindered the development of intermodalism and the optimal cross-mode use of transportation infrastructure. The transportation field presents challenges, but is exceedingly in need of the creation of an integrated and unified information community. The art and science of transportation network modeling has been developed through annual transportation modeling conferences and the annual TRB conference. The work in this thesis is attempting to create one small foundation stone in the direction of a wider transportation information community concerned with the management of network data. This wider goal can most logically and efficiently work with a set of common terms, definitions, and perhaps more importantly (as a lexicon can always be created) common information infrastructures.

Those who concerned to improve the operation, planning and management of transportation are thus vitally concerned with locational analysis. Transportation thus shares a very strong concern with locational analysis, in common with the disciplines of Geography and Urban Planning.
Transportation was one of the first communities to adopt computer-based analysis methods (e.g., The Chicago Area Transportation Study models of the mid 1950's). It thus created one of the first computer-based information communities. The art and science of transportation network modeling. However, the transportation community was relatively slow compared to other disciplines in the mid-1980's to adopt and adapt GIS tools. One reason for this was that GIS at the time poorly handled network data. Another reason was that the transportation community presented a diverse set of business needs that vendors of GIS tool-sets had trouble in clearly identifying the core business needs. The undertaking of this thesis, is again a reflection of this continuing need. Unlike other Geospatial communities, traditionally much transportation data management has been done in one spatial dimension – indexed by linear referencing systems. Different GIS vendors have taken alternative detailed approaches to the supply of foundation GIS tool-kits. This has made the transfer of network-based data between different vendor and application tool-kits more difficult than ideally should be (see Figure 16).

**Figure 16 Transportation Interoperability Issues**

![Vendor A to Vendor B](image)

Much of the core business of transportation involves the management and analysis of location: Where are the structurally deficient bridges? Where are the sections of state highways where alligator cracking index higher than 0.2? What (where) is the shortest route from A to B?

The effective cross-functional analysis of transportation has been stymied to date because many applications were "stove-piped" (or, "islanded"). In a state DOT, for example, as many as 100 applications convert, store, manage, and analyze transportation data. However, many of these applications were developed completely independently, often creating duplicate islands of both software and data. Asking the basic question, "how many miles of state maintained roads are there in the state," to three different groups within the DOT, would often generate three different answers. Traffic count data – one of the most basic data items of a DOT – would be stored in as many as 20 or 30 places within the DOT.

To help facilitate the transportation community about opportunities utilizing "off-the-shelf" tools to assist with operated functions, a number of educational and training opportunities have been available. For example, the US DOT National Highway Institute (NHI) offers transportation agencies a three-day course, "Introduction to Implementing Geographical Information Systems." To promote the benefits of information integration and interoperability, the FHWA offers a two or three-day course, "Integrated Transportation Information Systems" (Demonstration Project 113). The workshop is divided into sessions for CEOs, managers, and practitioners. Both courses are offered free of charge on-site by US DOT to public transportation agencies. The annual AASHTO GIS-T Symposium met last April for the tenth year running. Typically, over 300 registrants attend this event. The Symposium has been an important forum for the GIS-T
The Symposium is co-sponsored by a wide selection of the transportation and geoprocessing communities (US DOT, HEEP, URISA, etc.). The course sand Symposia have helped spread the message, but still today by common observation interoperability problems in transportation from a management perspective present a major problem (Lewis and Fletcher, 1999).

3.5.8.3 Transportation Networks

Transportation as whole is concerned with the setup and analysis of networks. As noted, transportation networks may be analyzed from two perspectives:

1. The form and characteristics of the network itself
2. The flows on the network

Table 11 shows transportation information community views is summarized from the California Transportation Plan 1993.

**Table 11 Transportation “Information Views” II**

<table>
<thead>
<tr>
<th>MODE OR FORM</th>
<th>MODAL OR COMMUNICATION NETWORK</th>
<th>NETWORK COMPRISED OF</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 ROADs</td>
<td>Local Roads</td>
<td>Streets and roads</td>
</tr>
<tr>
<td></td>
<td>Regional Roads</td>
<td>Major arterial; interstate</td>
</tr>
<tr>
<td></td>
<td>Inter-region and National roads</td>
<td>National Highway System, interstate highways, and interregional state highways</td>
</tr>
<tr>
<td>2 MASS TRANSIT</td>
<td>Bus</td>
<td>Local and regional travel lines</td>
</tr>
<tr>
<td></td>
<td>Light Rail</td>
<td>Local and regional commuter rail lines</td>
</tr>
<tr>
<td></td>
<td>Heavy Rail</td>
<td>Heavy rail; Soon) high speed rail</td>
</tr>
<tr>
<td>3 AVIATION</td>
<td>General aviation</td>
<td>Local airports</td>
</tr>
<tr>
<td></td>
<td>Regional travel</td>
<td>Major airports</td>
</tr>
<tr>
<td></td>
<td>Inter-regional and international</td>
<td>National and international airports</td>
</tr>
<tr>
<td>4 WATER</td>
<td>Local Waterways</td>
<td>Local marinas, seaports, and ferries</td>
</tr>
<tr>
<td></td>
<td>Inter-region</td>
<td>Inter-regional channels and international seaports</td>
</tr>
<tr>
<td>5 BIKE</td>
<td>Local and regional roads</td>
<td>Streets and roads and major arterial</td>
</tr>
<tr>
<td></td>
<td>Bikeways</td>
<td>Dedicated ROW</td>
</tr>
<tr>
<td>6 COMMUNICATION NETWORK</td>
<td>Telephone</td>
<td>Copper wire</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Fiber Optic</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Radio waves</td>
</tr>
<tr>
<td>7 PIPELINE</td>
<td>Pipelines</td>
<td>Gas</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Water</td>
</tr>
</tbody>
</table>
Networks are fundamental to all modal branches of transportation. Transportation Planning, Engineering and Science focuses on making more efficient the flow of good and people on transportation networks.

The most vital and core part of transportation service provision and analysis is typically focused on (or around) some type of transportation network. Networks are thus the backbone against which transportation services are demanded and supplied, as well as analyzed. As it is a field of especially strong concern to LRS, a little further attention here is given to transportation networks, the current field focus of transportation, and ITS.

Transportation specialists focus in the management and analysis of these networks, and have developed their own languages, operating terms, and worldviews. How a highway engineer, transit planner, and traffic flow analyst think of, for example, a route is similar, but, also, very different. In an integrated transportation environment, we might thus think of transportation being one information community. However, in operation and analysis, modal communities have only been partially connected, and therefore transportation has been, in effect, a set of information communities.

The analysis of network-related data is key, but of course not unique, to transportation. Other areas are equally concerned with networks; for example, Telecommunications, information Systems and Utilities. Fundamentally, in analysis terms, many of the basic analysis units are common. However, there are different business focuses, emphases, terms, and detailed analysis units and methods. OGC is attempting to put together a common architecture that will go across fields.

Transportation to date has traditionally been more analytically concerned with managing the flows on a network that inventorying and describing the network itself. Flow algorithms are covered in depth on Transportation Masters degree programs, but a deeper analysis of what is a network and, in particular, the spatial analysis of networks themselves, has traditionally not been covered. This thesis attempts to address this imbalance and is an arguably first attempt to do this in some fuller frame.

Many statistics have been used in the analysis of points and polygons. Network statistics have generally been given much less attention. However, they can be quite important when characterizing a single network (or sub-network) or when comparing networks. Networks can be compared in terms of for example:

1. Size
2. Connectivity, and
3. Compactness

For a network of \( n \) nodes it is possible to characterize the potential Size of the network by:

**Directed Links:**
1. The minimum number: \( n-1 \)
2. The maximum number: \( n \times (n-1) \)

**Undirected Links:**
1. Minimum: \( n-1 \)
2. Maximum: \( n^* \frac{(n-1)}{2} \)

Other such measures provide statistical indications of connectivity and compactness. Relative connectivity may be measured for example by taking measures of:

1. The number of links divided by the number of nodes.
2. The average valence of all nodes.

A compactness measure is the number of links in a shortest path. Various other more complex measures have been formulated to further describe networks. The above measures can all be used for example to determine the similarity of networks.

Network simplification is the construction of less detailed networks from more detailed networks. The need to present networks at different level of detail can arise both within and across transportation applications. Network simplification techniques include extraction, aggregation and abstraction. Network extraction is the process of withdrawing some portion of a network on the basis of some set criteria (e.g., link property, etc). Network aggregation is the creation of a new network by breaking the existing network into a distinct set of links and representing each set by one new link in the new network. Network abstraction is the creation of a new network with similar characteristics to old networks but with fewer links and nodes. All three result in the reduction of the number of links and nodes in a network. The attributes of resultant networks can be selected by a number of functions, e.g., average, weighted average, sum, Maximum, Minimum,” Choose”, etc.

Network conflation is the process of creating new networks from two or more base networks on the basis of attributes (e.g., street names), topology (e.g., node or link characteristics) or geometry (e.g., link shapes). The sequence of passing from a reference coverage (with for example poor spatial resolution but high quality attributes) and a target coverage (with for example accurate coordinates but no attributes) is shown in Figure 17.

**Figure 17 Network Conflation**
A review of network characteristics and statistics was provided in Lewis and Petzold (1993), drawing on the work of Bernstein (1990) and others. Appendix D of this thesis contains some further description of network summary statistics drawn from that material.

3.5.8.4 Intelligent Transportation Systems (ITS)

ITS comprises a number of vehicular and highway-based technologies to expedite vehicular and personal travel. The technologies include:

1. Advanced traffic management systems (ATMS)
2. Advanced traveler information systems (ATIS)
3. Advanced vehicle control systems (AVCS)
4. Commercial vehicle operations systems (CVOS)
5. Advanced public transport systems (APTS)

Drane and Rizos provide a review of positioning systems in ITS (Drane and Rizos, 1998). They note that positioning systems play a key role in ITS Architecture (the formalized systems design of which has been the focus of considerable private sector and public sector USDOT funding through ITS America).

Dane and Rizos note that positioning systems have a key uses and roles to play in:

1. In-vehicle navigation
2. Use of probe vehicles (that is, one used explicitly for traffic monitoring and data gathering purposes) to assist dynamic route guidance
3. More efficient computer-aided dispatch
4. Use of radar for collision avoidance
5. Radar used for automated cruise control
6. Automated traffic control systems, which use loop control detectors, etc.
7. Stolen vehicle recovery by systems that allow vehicle tracking
8. The efficiency of distress alarms to locate an emergency
9. Dynamic bus information systems

The topic of ITS needs and uses for LRS is covered further in this thesis through the inclusion of an ITS field expert in the expert Panel. The topic is not considered still further here as in short:

1. 1D versus 2D: Most of the above ITS applications and uses are, primarily, operational, real-time, two-dimensional applications, based on the use of GPS technology. Such applications do however often involve the locational “snapping” of 2D coordinated to a linear network.
2. Thesis Focus: The effective focus of the thesis becomes more the consideration of the management of data that is relatively static through time.
Certainly, if the topic of "positioning in transportation" had been taken, the requirements of ITS would be paramount. 6

The ITS community consists largely of ex-defense contractors; the "GIS-T" community consists of transportation planners and engineers; these communities have separate conferences and professional affiliations and interaction between them has been relatively limited to date. The use of wireless internet combined with GPS will dramatically improve onboard vehicle use and communications and other ITS applications in the next two to three years (Hada, et al, 2000).

ITS is focused on maximizing the efficiency of vehicle operations and has been the focus of much transportation research initiatives in recent years.

The above sections have focused on the "locational disciplines. The next section deals with other discipline viewpoints that have relevance to a wider appreciation of LRS.

3.5.9 GIS (Geographical Information Systems)

A GIS may be defined as a computer-based system for the acquisition, recording, organization, retrieval and display, and dissemination of spatial information. In theory, it does not require a computer – one could for example use a system of Mylar overlays - but in practice GIS is computer-based. However, it is probably fair to say that most of the thrust associated with GIS to date has been on gaining data and getting base systems reasonably populated and operational. Certainly, this has been the major concern in the field.

From their genesis in university research labs in the 1970's, GISs became more generally available in the 1980's. Their increased use has led to an attempt to academise the subject. There are several Masters programs in GIS and many Planning and Geography programs offer GIS modules. A review of the literature on GIS certainly points to a growing field of spatial theory, particularly in for example spatial database design and spatial operations (NCGIA, 1999).

Gradually, a wider theoretical basis has been put in place for GIS. In the US most of this work has been undertaken through the NCGIA-related activities. This umbrella organization has supported major multi-year initiatives in accuracy and uncertainty in spatial data, cognition ("human factors") and modeling and representation. The NCGIA since 1988 has held a number of conferences and research seminars on spatial matters.

A essential technical consideration of GIS is that in their early emphasis they were in first focus "polygon processing systems" or "polygon overlay processors" (POP). The technology was generic: the polygons in question could be zones of soil types, forestry zones, census tracts, or city parcels. The key utility of GIS was to overlay polygons so that the intersections (spatial unions, etc.) of various polygonal sets could be identified and presented in a much quicker way than manual techniques would facilitate. The important advantage of this was the ability to undertake "what if" analyses with a speed and dexterity that was not possible before.

6 The announcement by the White House on May 1, 2000 that Selective Availability (SA) would be switched off will dramatically improve the accuracy with which positional signals can be gained in real time. President Clinton in his address on the matter specifically referred to ITS Applications as a major beneficiary of the decision. (White House, 2000).
GIS only in a limited way considered network data until the 1990’s. This led to the creation of GIS-T, as covered in the next sub-section. Over one hundred research papers on spatial matters have been prepared (which may be referenced through www.ncgia.ucsb). None of these papers deals directly with linear spatial location referencing.

### 3.5.9.1 Geographical Information Systems for Transportation (GIS-T)

GIS as originally conceived in the late 1970’s and 1980’s focused on the analysis of polygons or areas. It gave less attention to networks, the prime focus of transportation.

The use of spatial processing technologies in transportation agencies led to efforts to enhance and extend GIS for Transportation. This field with the help of workshop run by the author and others, generally became known as “GIS-T”, or, “Transportation GIS”. The annual AASHTO Symposium, the field institutional forum, has now met for 12 years and draws approximately 400 to 500 people each year.

Such field interest has led software vendors to amend and extend their tools and supported data structures for transportation purposes. The need to add new network data management tools was required in part because of a basic realization that many do not have even today in the GIS field. As GISs were built essentially as a polygon overlay technology, it is not readily possible to do network overlay (or, for that matter, point overlay). Points cannot be readily overlaid because in short of the issue of defining a generic enough level of spatial “identicalness”, or, “close enough to”, for a computer to numerically directly match. These closeness measures will always be application-specific. The point overlay problem must for example be generally be converted into “point within a buffer zone (polygon)” problem. For similar reasons, it is not possible in current COTS GIS to directly spatially integrate networks (though see later section on “Conflation”), or, merge attributes from similar networks. Thus, it was important to find other approaches – which would include linear approaches – to facilitate the management and integration of data on one base network.

To meet such needs, and the most significant development of GIS-T, in the 1990’s “Dynamic Segmentation”(DS) tools were introduced. The term has become somewhat with the wider set of tools used to manage and analyze spatial network data, though provides core functionality to introduce LRS to GIS. “Dynamic Segmentation” is the prime example of a new functionality added for explicitly transportation purposes (see further details in Section 4.4), though the tools have found some uses in other domains. The provision of such tools has lagged the field user requirements described later in Chapter 6. While DS tools of version one variety were provided in the early 1990’s, most vendors appear to have put relatively little additional effort into developing “version two” dynamic segmentation tools. The major provider of GIS software has also become a provider of educational materials on GIS, which over the years have become more detailed and technical, as well as providing more network focused texts (for example, see Zeller 1999 and Lang, 1999).
3.5.10 Critique of the Contributions of the Locational Sciences

Table 12 provides a brief summary of issues and consideration relevant to LRS that may be drawn from the academic and professional fields reviewed above.

Table 12  Locational and Informational Sciences Contribution

<table>
<thead>
<tr>
<th>DISCIPLINE</th>
<th>PRIME FOCUS</th>
<th>POSSIBLE RELEVANCE TO LRS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1  Geography</td>
<td>Understanding spatial relations</td>
<td>Contextual setting</td>
</tr>
<tr>
<td></td>
<td></td>
<td>A wider, normative view of problem</td>
</tr>
<tr>
<td>2  Urban and Regional</td>
<td>Organizing spatial relations</td>
<td>Proscriptive view</td>
</tr>
<tr>
<td>Planning</td>
<td></td>
<td>Planning Requirements</td>
</tr>
<tr>
<td>3  Civil Engineering</td>
<td>Constructing physical relationships</td>
<td>Highway and transportation network design and construction details (to geometric form)</td>
</tr>
<tr>
<td>4  Surveying</td>
<td>Measuring spatial relations</td>
<td>Measurement issues (accuracy, precision)</td>
</tr>
<tr>
<td>5  Information Systems</td>
<td>Acquiring, storing, analyzing (spatial) data</td>
<td>Data structures and processes for linear data; processing models;</td>
</tr>
<tr>
<td>6  Transportation</td>
<td>Understand, organize, collect, present transport spatial data</td>
<td>Integrated transport view</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Transport data and information requirements</td>
</tr>
</tbody>
</table>

The above table indicates that all of the above fields have a role to play in a wider consideration of LRS. Until recently, there has been little published literature directly on the topic of LRS. It has been a possible constraint on the field that of the existing literature, the review conducted (see later sections in this chapter) indicates that to date that many analyses have been conducted primarily from one main academic viewpoint or field profession view. A particular gap may be the rich history of the consideration of the nature and form of geographic data and the wider history of use of geographic models. This thesis attempts to make a first attempt at drawing on such a wider disciplinary framework.

3.6 The Art and Science of Modeling

A model is an abstract description of a system or a process – a simplified representation that promotes understanding and enables simulation (Muller, 1997). Modeling is “the process of formalizing our framework for interpreting the world around us by abstracting from reality that is otherwise too complex to understand” (Bradley and Schaefer, 1998). Modeling is an attempt at simplification that means that information can be lost. The term “modeling” is often used as a synonym for analysis or the decomposition into simple elements that are easier to understand.
Modeling is an activity carried out by many professional areas, e.g., economic models, financial, behavioral, etc. Here we are concerned with the activity of spatial modeling. There are existent professional disciplines of “systems modelers” and “network modelers”. Network modelers may in fact be modeling communication networks, computer networks, semantic networks or transit networks. Transportation network models are the profession of modelers who know how to set-up operate transportation models, and engage in such activities as O-D estimation, cordon compression, screen line estimating, etc.

Functional modeling decomposes tasks into functions that are simpler to implement. Object-oriented modeling decomposes systems into collaborating objects. There are many types of models and many classifications. The intent is here is not to provide an exhaustive review of models. It is however intended in this section and chapter as a whole to very briefly indicate:

1. A basic distinction or taxonomy of “models”
2. Where a LRS model might best fit or be considered
3. Where wider inference on “LRS models” may be gained.

Systems analysis is also a generic activity that has used modeling extensively.

3.6.1 Systems Analysis

A system is intended to satisfy predefined goals or functions. A system could be a pavement management system or a military payload delivery system.

The formal discipline of Systems Engineering grew out of military weapons systems procurement in the 1960’s. Grady (1993) a leading field proponent quotes the 1960’s Air Force Systems Engineering Management Procedures manual, “No two systems are ever alike in their development requirements. However, there is a uniform and identifiable process for logically arriving at system decisions regardless of the system purpose, size of complexity”. This process uses various kinds of models.

Two elements of Systems Engineering are Systems Requirements Analysis and Systems Analysis. Systems Requirements Analysis is a structured or organized methodology for identifying:

1. An appropriate set of resources to satisfy a system need, and
2. The requirements for those resources that provide a sound basis for their design and selection

Oliver, et al (1997) note that Systems Engineering is important because it:

1. Matches the product to the marketplace
2. Defines the components to enable the designers to design and build them
3. Determines most of the design choices affecting system cost and performance
4. Ensures the components will integrate successfully and perform together as required
5. Provides specifications free of errors, since errors are very expensive to correct in the latter stages of design and production.
The general concepts of Systems Engineering in the 1980's and 1990's became increasingly applied to software engineering as one example of systems engineering. Martin and Odell are amongst the leading proponents (Martin and Odell, 1992).

Models briefly alluded to above have to be practically implemented in a computer environment. This imposes it own rigor. Key distinction here is between models use for formalizing our understanding of:

1. **Process models** - for example models that try to replicate the process or activities of transportation or planning systems
2. **Data models** – that in static form model the relationships between data elements (such as needed for database design)

### 3.6.2 Planning and Transportation Models

Planning and transportation models simulate human activities. Lee (1973) denotes three classes of models used in planning. These are:

1. **Descriptive Models**: They reveal much of the structure of the urban environment, reducing the apparent complexity of the observed world to coherent and rigorous language of mathematical relationships.
2. **Predictive Models**: They simulate future rather than current situations. They are sometimes called “forecasting models”.
3. **Planning Models**: These are “normative” models. They are extensions of forecasting models that have built in goals and objectives.

Various authors describe in depth the various types of planning modeling activities that have been undertaken. (Krueckeberg and Silvers (1974), Miller, et al, 1998). No more general taxonomy has been found. These include models for:

1. Population models
2. Location and travel behavior
3. Land use activity projection
4. Transportation travel forecasting.

Figure 18 shows the traditional transportation network modeling process that is undertaken in all urban areas above 50,000 in the US.

Planning level models as noted earlier had a period of popular academic attention in the 1960's. Coincident with the publications of Douglas Lee’s landmark paper, “Requiem for the Large Scale Model” (Lee, 1973), the relative absolute popularity of planning models in academia somewhat diminished. However, the practice of land use (e.g., Lowry) and transportation (e.g., UTPS style) modeling continued in the field in many agencies.
Table 13 below a brief taxonomy of locational analysis models.

**Table 13 Classification of Geography, Planning and Transportation Models**

<table>
<thead>
<tr>
<th>TYPE OF PLANNING OR LOCATIONAL MODEL</th>
<th>PURPOSE</th>
<th>EXAMPLE OF MODEL</th>
<th>EXAMPLE APPLICATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 <em>Descriptive</em></td>
<td>Describe current situation</td>
<td>Potential Model, Gravity model, Linear model, Diffusion models, Central place models</td>
<td>Analysis of spatial (e.g., land use) patterns</td>
</tr>
<tr>
<td>2 <em>Predictive</em></td>
<td>Formulate future scenarios; forecasting</td>
<td>Combined land use transportation models</td>
<td>Lowry model: estimate land use changes. Transport model: estimate traffic flows</td>
</tr>
<tr>
<td>3 <em>Planning or Normative</em></td>
<td>Optimization</td>
<td>Linear Programming</td>
<td>Finding an optimal location for a new business</td>
</tr>
</tbody>
</table>
In recent years there seem to have been a resurgence of modeling efforts using more sophisticated and integrated approaches. This has included:

1. The proposition of new conceptual frameworks for integrated transportation modeling (Miller, et al, 1998). See for example Figure 19.
2. Improved bases for modeling. The USDOT has had an ongoing travel Model Improvement Program since 1992. (Shunk, 2000)
3. The potential use of models to deal with traffic congestion and energy consumption.
4. The use of newly available local data to add sensitivity to existing models and approaches.

The use of integrated urban models (as shown in Figure 19) is having something of a renewed focus of attention at the present time, as exemplified by Miller (1998).

**Figure 19 Integrated Modeling: General Schematic Flow Chart**

(From Miller, 1998).
A data model is a conceptual representation of the data structures that are required by a database. The data structures include the data objects, the associations between data objects, and the rules that govern operations on the objects. The data model for a single system or an application field is usually called an application data model. The data model focuses on what data is required and how it should be organized rather than what operations will be performed on the data.

There are a number of types of data models. These are usually taken to be (in a typical sequential order of application):

1. Conceptual
2. Logical
3. Representational
4. Physical

A Conceptual Data model is a high-level data model. It may be an entity relationship model or an object-oriented model. It shows in more abstract format the relation between key items. While an abstraction of the real world, the result of conceptual modeling is quite concrete in a nature. The organization chem. Created at this stage contains the information content of the database, not a plan for the physical storage.

Logical data models have a data or system user focus. The map the relationships between data entities. They are not concerned with implementation details or technology, which will be focused on in the set-up of physical data models (for example, covering details of data storage, etc). Logical data models can be one of several general forms, sometimes called representational data models, (e.g., relational, hierarchical, network, object-oriented, etc.). The logical data models are in form that can be readily interpreted into computer application.

Physical models are required by those who actually install, set-up and maintain (typically computer-based) systems. Table 14 makes distinct logical and physical data models.

**Table 14 Logical Versus Physical Data Models**

<table>
<thead>
<tr>
<th>The Logical Model</th>
<th>The Physical Database Design</th>
</tr>
</thead>
<tbody>
<tr>
<td>Includes all entities, relationships, and attributes (and their information types) whether supported by a technology or not.</td>
<td>Includes tables, columns, keys, data types, validation rules, DB triggers, stored procedures, domains, and access constraints (security)</td>
</tr>
<tr>
<td>Uses business names.</td>
<td>Names may be limited by the DBMS.</td>
</tr>
<tr>
<td>Captures and records information necessary for the business.</td>
<td>Includes technology-specific data elements such as flags, switches, and timestamps.</td>
</tr>
<tr>
<td>Includes unique identifiers.</td>
<td>Includes primary keys, foreign keys, and indices for fast data access.</td>
</tr>
<tr>
<td>Is normalized to at least 3rd normal form.</td>
<td>May be de-normalized to meet performance requirements.</td>
</tr>
<tr>
<td>Does not include any redundant data.</td>
<td>May include redundant data elements.</td>
</tr>
<tr>
<td>Does not include any derived data.</td>
<td>May include results of complex or difficult to recreate calculations.</td>
</tr>
<tr>
<td>Business experts drive the model.</td>
<td>DBS drive the model</td>
</tr>
</tbody>
</table>
Data models are intended to:

1. Guard against semantic ambiguities
2. Provide a common framework of understanding.

One form of data model is the entity-relationship diagram (ERD). An ERD diagram consists of entities or the things we are interested in and a description of the relationship between those things. An example ER symbology used is in Figure 20.

**Figure 20 Typical ER Diagram Entities and Relationships**

(Adopted from Butler and Dueker, 2000)

<table>
<thead>
<tr>
<th>ENTITIES</th>
<th>RELATIONSHIPS</th>
</tr>
</thead>
<tbody>
<tr>
<td>Feature</td>
<td>Real-world features</td>
</tr>
<tr>
<td>Graphics</td>
<td>Cartographic objects</td>
</tr>
<tr>
<td>LRS</td>
<td>Datum objects</td>
</tr>
<tr>
<td>Network</td>
<td>Topological elements</td>
</tr>
</tbody>
</table>

Entities can be both real and conceptual. In general, real-world features are represented on maps using cartographic objects.

Figure 3 summarized a number of levels of abstraction in modeling between the real world entities and detailed database schemas or program code. There are few good texts of data modeling. Tillman (1993) is one of the most respected and clear on the general process, but suffers from being focused on the entity-relationship model (bypassed by OO) and being pre-modern modeling language (UML, as described below).

Table 15 gives a comparison of a Geographic Information System and a Transportation Model. The GIS relates more closely to a generic data model while the transportation model attempts to capture the process of transportation planning.

### 3.6.4 Spatial Modeling

Spatial (data) Modeling refers to the “design process for abstract representation objects describing the geometric structure, extent, and shape of objects in space, for their relationships to other representation objects, and for their relationships to the space within which they are located”. (Schneider, 1997). Objects created in such a process are called spatial objects, and typically have been identified as points, lines and polygons (or regions).
Table 15 Comparison of GIS and Transportation Model

<table>
<thead>
<tr>
<th>Geographic Information System</th>
<th>Transportation Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Multi-purpose</td>
<td>Single purpose</td>
</tr>
<tr>
<td>Data driven</td>
<td>Model-driven</td>
</tr>
<tr>
<td>Geographic context</td>
<td>Abstract context</td>
</tr>
<tr>
<td>Many topologies</td>
<td>Single topology (link-node)</td>
</tr>
<tr>
<td>Chain structures</td>
<td>Link-node structure</td>
</tr>
<tr>
<td>Spatially-indexed</td>
<td>Sort-indexed</td>
</tr>
<tr>
<td>Many fields</td>
<td>Few fields</td>
</tr>
</tbody>
</table>

Reviews of methods of spatial data modeling are provided by Schneider (1997), Samet (1990), and Zeiler (1990).

A distinction is made between spatial or location analysis and spatial modeling. Locational analysis as described earlier through section 3.5. Spatial models (as here defined) provide an ordering of the data so that it may be represented in the database or computer; locational or spatial analysis (using a higher level or type of spatial model, such as a gravity model) provide a means of understanding real world relationships between spatial entities.

In Chapter 2, it was noted that Schon referred to practitioners “worldmaking”. Others have referred to this as the creation of “microworlds” in the set up of models. Smyth proposes an ontology of a spatial modeling microworlds which comprises of just five components (Smyth, 1998). These are shown in Table 16:

Table 16 Model Ontology Specification

<table>
<thead>
<tr>
<th>ONTOLOGICAL ELEMENT</th>
<th>DESCRIPTION</th>
<th>CHOICES</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Contents</td>
<td>Things being modeled; structure</td>
<td>Identity: Field, entity, alternatives, hierarchies</td>
</tr>
<tr>
<td>2 Temporal structure</td>
<td>Event-sequential form</td>
<td>Order: Absolute, relative, alternative</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structure: Continuum, framed</td>
</tr>
<tr>
<td>3 Geometry</td>
<td>Spatial relationships or spatial structure</td>
<td>Order: Dimension</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Structure: Continuum, framed</td>
</tr>
<tr>
<td>4 “Physics”</td>
<td>Rules of behavior of the contents or entities under time and geometry</td>
<td>Type: None, naïve, Newtonian, special</td>
</tr>
<tr>
<td>5 Logic</td>
<td>Rules of inference</td>
<td>Type: None, first-order predicate calculus, modal, dynamic</td>
</tr>
</tbody>
</table>
Smyth states, “Geographic modeling based on components has the potential to facilitate the integration of existing models of the earth .... One way to ensure that the components form a coherent and consistent model is to follow a methodology.... where the link between ontology and implementation are explicit .... Perhaps the most exciting aspect of this approach is the possibility of very detailed and complete models arising from the collaborative work of many individuals” (Smyth, 1988).

LRS is one type of spatial data model. Appendix G reviews an alternative spatial model framework for LRS than that used traditionally to date.

3.6.5 Overview of Object-Oriented Approaches to Modeling

Geographic data (consisting of attributes, geometry and topology) can be stored, viewed and analyzed in at least three main ways. These are:

1. **The Relational Table Method.** Here attributes and geometry are stored in columns of a relational database. New software from major database vendors basically takes this approach.

2. **The Simple Feature or Coverage Method.** Here simple geographic features (e.g., points, lines and polygons) are stored in the GIS as homogenous sets. “The generic behavior supported by the coverage data model enforces the topological integrity of the dataset”. (Zeiler, 1999).

3. **Object Model Method.** Here spatial objects encapsulate the topological, geometric and attribute properties of the object.

Much process and data modeling work has moved to the Object-oriented paradigm. Objects encapsulate both data and processes. There are at least four manifestations of OO techniques and technologies. These include:

1. **OO modeling techniques.** This can include OO analysis and design. These are intended to provide benefits to application designers. These are intended to principally benefit the application or system designer.

2. **OO programming and programming languages.** These include C++ and Java. They are intended to provide programmer benefits.

3. **OO Database Management.** They provide complex data types and DBA benefits. Many of the major relational database vendors now offer OO extensions, and other vendors offer exclusively OO focused databases.

4. **OO Interfaces.** A Macintosh or windows interface is an OO interface.

A very brief review of Object-Oriented (OO) approaches is provided here. The fundamental construct of OO is the object. Object-orientation is the organization of systems or software as a collection of objects that incorporate both data structure and behavior. An object consists of a set of attributes (the data components) describing its state and a set of operations (the procedural components) defining its behavior. It is an atomic entity formed from the union of state and
behavior. Objects can be “concrete” (e.g., a bus) or “abstract” (e.g., scheduling policy). An example of a road object might be as shown in Table 17.

**Table 17 Example Road Object**

<table>
<thead>
<tr>
<th>ROAD</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attributes:</td>
</tr>
<tr>
<td>- name(s)</td>
</tr>
<tr>
<td>- road numbers</td>
</tr>
<tr>
<td>- number of lanes</td>
</tr>
<tr>
<td>- intersections</td>
</tr>
<tr>
<td>- location coordinates</td>
</tr>
<tr>
<td>- graphic representation</td>
</tr>
<tr>
<td>- pavement type</td>
</tr>
<tr>
<td>Methods:</td>
</tr>
<tr>
<td>- show no. lanes at a location</td>
</tr>
<tr>
<td>- name at a location</td>
</tr>
<tr>
<td>- find intersect with road x</td>
</tr>
</tbody>
</table>

The following characteristics are usually required of an object-oriented approach:

1. **Encapsulation** (or identity). The data attributes and operations are said to be “encapsulated” in the object, so that the details of the object can be abstracted from knowing the details of its implementation. The operations may be **public** or **private**.

2. **Classes** (or classification). Classification occurs when objects with the same behavior and data structure are linked together. A class is like a blueprint for a set of objects.

3. **Inheritance**. This is the sharing of attributes and operations among classes based on a hierarchical relationship.

4. **Polymorphism**. This means that the same operation may behave differently in different classes.

Objects can be linked together through both inheritance as well as explicit **association**. Associations represent structural relationships between classes and objects. Associations can be further defined by:

1. Naming the association (e.g., “manages”).
2. Naming the role played by the objects (e.g., “manager”, “managed”).
3. Defining the multiplicity, in terms (e.g., 1 instance, 0 to infinity instances, etc).

Molenaar (1998) provides the fullest technical text generally applying object modeling to spatial objects. He touches on graph theory and the spatial modeling of line objects, but does not formally consider networks or linear referencing systems.
Object-oriented modeling is similar to ER logical data modeling. A comparison is shown in Table 18 below.

### Table 18 OO and ER Logical Data Diagrams


<table>
<thead>
<tr>
<th>Object-Oriented Modeling</th>
<th>ER Logical Data Modeling</th>
<th>Differences</th>
</tr>
</thead>
<tbody>
<tr>
<td>Object</td>
<td>Entity</td>
<td>Object includes processes</td>
</tr>
<tr>
<td>Attribute</td>
<td>Attribute</td>
<td>None</td>
</tr>
<tr>
<td>Link</td>
<td>Relationship</td>
<td>Similar</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Associations the same;</td>
</tr>
<tr>
<td></td>
<td></td>
<td>-Inheritance the same as subtype/supertype except data modeling does not include operations</td>
</tr>
<tr>
<td>Encapsulation</td>
<td></td>
<td>No corresponding logical data modeling concept</td>
</tr>
<tr>
<td>Object class</td>
<td>Entity type</td>
<td>None</td>
</tr>
<tr>
<td>Object instance</td>
<td>Entity instance</td>
<td>None</td>
</tr>
<tr>
<td>Messages</td>
<td></td>
<td>No corresponding concept, since messages are process related</td>
</tr>
</tbody>
</table>

3.6.6 Modeling Language - UML

There were a number of different notations used in the 1990's to do Object Oriented design, modeling and analysis. Three more common methods were OOSE (Jacobson), OMT (Rumbaugh) and Booch Method (Booch). Attending many meeting on topics like LRS in the early to late 1990's, or at meetings of the Object Management Group (OMG) or the Open GIS Consortium (OGC), or in meetings on LRS, one was struck how communication was restrained by the *lack of a common model language and syntax*. A large part of many meetings was spent on model syntax or "language" issues.

To address this issue, the creators of the three main modeling languages or approaches agreed, under prompt from OMG, to form a unified data model language. The Unified Modeling Language (UML) is a synthesis of these three modeling methods starting from a synthesis that started in 1994 (Booch, Jacobson and Rumbaugh, 1998). It was adopted as the OMG standard in September 1997. UML is now in version 1.3. It has since become the industry accepted standard, and has been adopted by most of the major systems modelers and software houses in the US.

Some of the relevant goals of UML include:
1. Support higher level development concepts such as components, collaborations, frameworks and patterns
2. Provide users with a ready-to-use, expressive visual modeling language to develop and exchange meaningful models
3. Furnish extensibility and specialization mechanisms to extend the core concepts
4. Support specifications that are independent of particular programming languages and development processes.

UML provides for the creation of a number of types of diagrams. These diagrams are listed below with a short description. The exact use and utility if each diagram type is difficult to best comprehend in a short description, but the set of diagrams together represent a useful integrated toolbox for systems analysis and design. The UML diagrams are (Muller, 1997):

1. Activity. Represent the behavior of an operation of set of actions.
2. Class (or, class static structure). They show the static structure of the system.
4. Component. Represent the physical components of an application.
5. Deployment. Represent the deployment of components on particular pieces of hardware
6. Object . Represent objects and their relationships, and correspond to simplified collaboration diagrams that do not represent message broadcasts.
8. State chart. Represent the behavior of a class in terms of states.
9. Use-case. Represent the functions of a systems from the user’s point of view.

These set of diagrams allow for a whole set of activities that provide support in system specification and production, from user needs assessment to software generation. For many purposes the class diagrams (or static diagrams) will be the most used, as they most fundamentally shows the relationship between objects classes and between object classes and objects.

Each type of diagram has a standard symbology associated with it. In UML, the notation is different from that used for E-R diagrams shown above in Figure 20. For example, taking the Class Diagrams, the classes are shown by square boxes with three compartments. The first compartment contains the class name; the second compartment contains the class attributes and the third compartment its operations. The associations between classes, rather than being labeled with arrows and marks, may be labeled by characters and numbers to denote associations (e.g., 0, 0...1, 0...*, where * is infinity), or, by “nouns” (e.g, employer) or “verbs” (e.g., ‘employs”).

Since UML can be used for database modeling as well as software engineering it is surprising that Date in the latest version of his database classic (Date, 2000) gives only a few sentences side mention to it. There are now a number of available texts that do give a fuller treatment of UML. Martin and Odell (1998), long known as major leading proponents of object oriented modeling techniques, modified their seminal and standard field text in a version to include UML (Martin and Odell, 1998). The work remains strong in describing the use of Object-Oriented techniques, but as an early work in the field on the UML standard, is rather poor on UML. The OMG Unified Modeling Language Specification is complete, but very dry and poor in being more generally explicative – that is poor in describing OO modeling techniques. (Object Management Group, 1999). Muller (1997) provides a very readable treatment, and so does Fowler (2000) which has
become a standard field reference, especially in the new version. The text by Odell (1998) is a useful reference to some advanced UML modeling considerations and techniques.

Examination of this literature has indicated that an issue with all of the texts at the present is that they give poor explanation and example of the use of the different types of the different UML diagramming symbologies and conventions. For example, with Class diagrams, it is difficult for the average practitioner in all cases to quickly discern which type of association to use (association can be either, “plain association”, “aggregation”, or “composition”). Muller probably provides the most salient advice when he indicates that using the lowest form of the strength of association in any given case is probably the most appropriate (for example, “plain association”, rather than “composition”, which is defined as implying a physical containment of one class within another class, such as the physical containment of one engine within one car). As field experience of the use of UML grows, and in association modeling, further refinement in the advice and field examples given will greatly help field practitioners trying to reduce their field to most appropriate object model form. For example, in linear referencing, do we wish to represent a highway link as an association with a route, a part of “an aggregate” or “a composition”. Such questions example issues that are likely to be largely most appropriately answered by field experience and modeling intent, but may also benefit from input from wider data modeling experience.

3.6.7 Constraints of Modeling

Individuals who are experienced in the computer-level class of models, data modelers, may often be much less experienced of the wider literature and body of experience on process models in individual fields. Process or operational models are typically set-up and used by field experts. For example, there is an established community and profession of “transportation modelers”. Creating accurate data models requires an understanding of business or planning processes. Data modelers need to gain knowledge of a particular domain from the field expert to create data models. Formal techniques have been established to accomplish this.

Some of the constraints of models and modeling apply to both the process and data types of models described above. A number of critiques are available. The limitations of formal modeling as critiqued by Bradley and Schaefer (1998, p.35) takes a behavioral stance. Their general concerns with modeling are in summary:

1. Behavioral Assumptions: Because the formal modeling forces one to state theory in precise, logical and efficient manner, it creates a danger that only the mathematical assumptions will be stated, and the more behavioral assumptions in the model will lay buried, implicit, and perhaps unreasonable.

2. Choice of Variables: Modeling may bias of the statement of assumptions but also the choice of questions or variables to be explored.

3. Model Method Overplayed: The desire for generality can cause one’s method to be overplayed, such that the “modeling tail wags the substantive dog”.

4. Model Simplifications: Model use and familiarity seems to make the initial simplifying assumptions forgotten.
5. "Model Mania": The growth of desktop modeling tools encourages the use of modeling by those not fully trained in it.

Bradley and Schaefer while based more in a social science setting present a set of views in a larger framework which while available in some part before is extremely useful. Their concerns more fully mapped out in their book will be reviewed in the conclusions to this thesis.

How one models or thinks about space affects one's worlds view. Transportation planners and engineers typically think "linearly" about many transportation issues. Every map offers only its own perspective on the world, however objective it may appear to be, a perspective that applies a particular assertion of reality" (p.175, King, 1998). The form of transportation (linear) models thus has implications beyond just the immediate management of transportation data. For example, "the dominant mapping of Los Angeles is a repressive grid that inscribes lines of class and race repression onto country" (King, 1998). Maps that transportation engineers have completed have influenced their perspective of reality. Thus, the fact that much transportation analysis is done within "a linear concept" has wider implications for the way that much transportation planning and engineering work has been conceived and completed.

There is also a higher class of models, "users models" or mental models, which is appropriate to the conceptual models that individuals create. Users' models are the representations users may form of the computer system that they are interacting with. The appropriate understanding of user models can lead to the development of interfaces that are appropriate to efficient user interaction.

An additional theoretical area here of behavioral modeling is not reviewed hereon.

3.7 Chapter Summary and Conclusions

Location has been the concern of many academic disciplines. Dealing fully with locational issues can mean at the least drawing on more than one discipline and in some cases many of the disciplines briefly outlined in this chapter.

3.7.1 Progress Achieved

This chapter introduced many of the disciplines that bear on network analysis and potentially on LRS.

It also provided a brief consideration of the nature of the spatial data. This included that much of transportation data is "locationally rich", meaning that even relatively simple cases or problems, have many variations and exceptions.

It was seen that the different disciplines reviewing spatial matters have invented their own language. Any term in this field may be viewed as potentially "polysemous". This is particularly so with the term "network", as:

1. It made of the above elements (points, lines, etc), and
2. It may be semantically referring to:
   a) Infrastructure (as here)
A summary attempt at synthesizing some of the “spatial languages” reviewed in this chapter is shown in Table 19.

<table>
<thead>
<tr>
<th>DISCIPLINE</th>
<th>Term 1</th>
<th>Term 2</th>
<th>Term 3</th>
<th>Term 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimensions</td>
<td>“Point”</td>
<td>“Line”</td>
<td>“Route”</td>
<td>“Area”</td>
</tr>
<tr>
<td>0</td>
<td>0</td>
<td>1</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>1 Cartography</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
</tr>
<tr>
<td>2 Geography</td>
<td>point</td>
<td>line</td>
<td>route</td>
<td>area</td>
</tr>
<tr>
<td>3 Urban &amp; Regional Planning</td>
<td>point</td>
<td>line</td>
<td>route</td>
<td>area</td>
</tr>
<tr>
<td>4 Civil Engineering</td>
<td>vertex</td>
<td>chain</td>
<td>string</td>
<td></td>
</tr>
<tr>
<td>5 Surveying</td>
<td>point</td>
<td>chain</td>
<td>traversal</td>
<td>chain</td>
</tr>
<tr>
<td>6 Transportation Modeling</td>
<td>node</td>
<td>link</td>
<td>path, route</td>
<td>path, route</td>
</tr>
<tr>
<td>7 Information systems (computer graphics)</td>
<td>point</td>
<td>line</td>
<td>polyline</td>
<td></td>
</tr>
<tr>
<td>8 GIS</td>
<td>node</td>
<td>line segment, arc</td>
<td>Route traversal</td>
<td>polygon</td>
</tr>
<tr>
<td>9 Mathematics (Topology)</td>
<td>node 0 tuple</td>
<td>Arcs, links 1 tuple</td>
<td>string</td>
<td>Polygon 3 tuple</td>
</tr>
<tr>
<td>10 Mathematic (Geometry)</td>
<td>vertex</td>
<td>Line segment, edges</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

In their very full coverage of “Engineering Complex Systems”, Oliver et al (1997), provide a rigorous coverage of the whole systems engineering approach. However, they do also critically note, as a side comment:

“Modeling in no way substitutes for creative engineering thinking and problem solving. Creativity and new solutions come from the engineers. Modeling reduces their manual work and improves accuracy.”

This chapter has however noted the importance of data modeling in a field of polysemous objects or entities to:

1. Guard against semantic ambiguities
2. Provide a common framework of understanding.

Table 20 shows alternative location reference systems and the disciplines that use them.

**Table 20 Location Reference Schema**

(from Vonderohe, 1987)

<table>
<thead>
<tr>
<th>Location Reference System</th>
<th>Dimension</th>
<th>Datum Object</th>
<th>Reference Object</th>
<th>Location Specification</th>
<th>Transformation</th>
<th>Disciplines</th>
</tr>
</thead>
<tbody>
<tr>
<td>WGS84</td>
<td>3D</td>
<td>3D Cartesian Axes</td>
<td>GPS Satellite</td>
<td>X,Y,Z</td>
<td>X,Y,Z &lt;-&gt;theta, lambda, h</td>
<td>Surveying</td>
</tr>
<tr>
<td>NAD83</td>
<td>2D (Horizontal)</td>
<td>Ellipsoid</td>
<td>Horizontal control station</td>
<td>Theta, lambda</td>
<td>Theta, lambda &lt;-&gt; x,y</td>
<td>Cartography, Civil Eng., Geography</td>
</tr>
<tr>
<td>PLSS</td>
<td>2D (Non Mathematical)</td>
<td>Section Corner</td>
<td>Cadastral survey</td>
<td>Township, Range, Section, Aliquot</td>
<td>None</td>
<td>Cartography, Civ Eng</td>
</tr>
<tr>
<td>NAVD 88</td>
<td>1D (vertical)</td>
<td>Geoid</td>
<td>Benchmark</td>
<td>Elevation</td>
<td>None</td>
<td>Surveying</td>
</tr>
<tr>
<td>LRS</td>
<td>1D (Linear)</td>
<td>Anchor Point/ Anchor section</td>
<td>Traversal Reference Point</td>
<td>Offset along Anchor Section</td>
<td>LRM_i &lt;--&gt; LRM_j</td>
<td>Transportation</td>
</tr>
</tbody>
</table>

The different location schemas reflect the needs and opportunities of the different communities.

This chapter identified UML as a tool that facilitates with the creation of OO diagrams (but does not strictly imply use of one OO modeling technique). It can be used to create OO software models or OO database designs. Many data model software vendors now provide UML extensions. UML is thus an important tool for formally analyzing networks and LRS, given that many of the early meetings on LRS, lack of a common diagramming syntax was a major constraint to communication. UML is used in Appendix G to present some alternative LRS models and approaches.

### 3.7.2 Ten Key Observations

1. **Role of Definition of Networks and LRS:** LRS “sits on top of” networks. A precise definition of network is required to apply LRS.
2. **Highway Form Development:** Applying LRS on the Roman road system was more straightforward than on the more complex road systems that exist today.

3. **Messiness of Spatial Data:** All spatial data is inherently messy. This includes spatial networks.

4. **Domain Language Issues:** There is a domain classification problem with networks and network features. Classification in any domain depends on training and the formal domain one represents or reflects.

5. **LRS Ontology:** Terms used with network analysis mean different things to different practitioners (i.e., they are polysemous). The creation of a standard dictionary (and an ontology of objects) which is accepted by the wide transportation community appears to be key.

6. **Data Management View of LRS:** Transportation planning and much DOT transportation data management typically look at data in a more aggregate way than for example a Civil Engineering level of analysis level. This level of detail may be appropriate for many of the management applications briefly touched on in this chapter.

7. **Model Context:** In creating application models and data models one needs to be very aware of the context and limitations of those models.

8. **LRS Model Class:** LRS is a form of spatial data model.

9. **OO Methods:** OO approaches appear to have strong relevance to LRS.

10. **Further Research:** Further multi-modal and cross transportation information community research is required on a detailed ontology for LRS and networks.

### 3.7.3 Main Conclusions

The models that one builds of where one is in space are a factor of the science that one is trained in and using. This is also reflected in the model tools used to reference that space.

By looking at matters from different positions, we may be aided in potentially identifying new solutions. This is the attempt of applying the different research tracks in this thesis. Engineers' training may for example be most focused on applying (or, trying to apply) "in the box", known solutions, while others may bring synthesis of other relevant viewpoint and domain, but perhaps lack the rigor and practicality the engineer may bring. LRS solutions that are truly relevant to the wider communities may critically depend on such approaches.

In summary on this chapter, in terms of the LRS research topic, it has been the intent to describe:

1. A thorough and strong understanding of the transportation application domain is required.
2. A variety of disciplines that are placed to contribute to create new (or at the very least), “reinforced” or alternative ways of looking at the LRS issue.

3. Modeling approaches and tools that maybe appropriate.
3.8 Chapter References


Bryant, P.R. *Graph Theory Applied to Electrical Networks.* Graph Theory and Theoretical Physics, F.R. Harary (ed.), New York. 1967


White House, President Clinton. *Improving the Civilian Global Positioning System.* Press Release. May 1, 2000


4 Semantics and Technology for LRS

Servant:
Perhaps you have learned it without book but, I pray, can you read any thing you see?

Romeo:
Ay, if I know the letters and the language.

Romeo and Juliet. Act 1, Scene 2. William Shakespeare.

4.1 Chapter Purpose

The previous three chapters attempted to layout the wider frame for LRS. This chapter starts a process of a much more detailed level focus on LRS; it provides a review of the core field concepts of linear referencing. It further establishes the framework by which linear referencing is considered further in this thesis and a set of working terminology (i.e., “the letters and the language”, of the quote above). It thus further develops the LRS ontology started in the previous chapter. While the previous chapters have been more concerned with the identifying semantic views of LRS, this chapter is more concerned with semantic language.

It is not believed such a synthesis was attempted before. There has been some overview in passing to some of the concepts outlined here in other work (for example, see the papers produced by the modelers, represented in Chapter 5). However, it is believed that a fuller development of the framework and synthesis on LRS as presented here has not been readily available in full before. This chapter and the synopsis may therefore be of some wider utility.

This review has been drawn from:

1. Literature: Reference to the existing LRS field literature, such that it exists. This was mainly drawn from direct reference to DOT working documents (such as those gained for example from Idaho, 1995, Iowa, 1998, Kansas, 1993, Minnesota, 1992, 1994, and 2000, and Nova Scotia, 1999).
2. BTS LRS Compilation: It was also aided by the compilation provided on BTS CD of LRS papers (BTS, 1997).
3. The Case Studies: Several examples of the application of linear referencing are presented with direct reference to the case studies (which are presented in more detail in Chapter 6).
4. Field Visits: Other general field visits to transportation agencies carried out between 1990 to 1999.
5. Other Field Sources: This has included workshops and other activities carried out on LRS, including as carried out of this thesis.
As noted in the Conclusions to Chapter 2, the research that has been completed here has been an iterative process. This chapter in fact draws from several of the research tasks, not just desk study.

One of the wider purpose of this thesis is by reference to and examination of field example to show the variety of field circumstances that must be addressed by any Location Referencing Method (LRM). This chapter also includes a brief review of LRS:

1. **Technology.** The technology that LRS may be used in association with, and
2. **Data Models.** An introduction to the LRS data models is provided. These data models will be examined in more detailed in Chapters 7 and 9.

This chapter also draws heavily on in field experience in presenting participatory LRS workshops (Lewis, 1994, Lewis, 1995, etc). These were prepared and collated under a variety of circumstances including at major national transportation conferences such AASHTO GIS-T Symposium and the Transportation Research Board (TRB) annual meeting. Workshops were also presented at state DOTs with support from FHWA and the National Highways Institute (NHI).

Some of the concepts and ideas described in this chapter were first posited ten or twelve years ago. Initially, they were exploited and developed quite slowly. In the last two years, there has been an increasing and quite rapid pace of LRS interest and development (e.g., introduction of LRS at the database level in the last year, more accurate GPS in mid 2000, etc.) so that greater effort is required to fully keep abreast of even this relatively focused field.

### 4.2 A Definition of Linear Referencing

This section reviews in more detail LRS terms, methods, traversal organization schemas and the organization of control and event data. As an example of the issues and alternatives faced in the field, a review of the possibilities for coding ramps is given.

#### 4.2.1 Key terms

While there is some confusion in the literature, one area of general agreement is with the following two terms (originally from Baker and Blessing, 1974):

**Location Referencing System (LRS).** The total set of procedures for determining and retaining a record of specific points along a roadway. The system includes the location referencing method(s) together with the procedures for storing, maintaining, and retrieving location information about points and segments on the roadways.

**Location Referencing Method (LRM).** The technique used to identify a specific point or segment of a roadway, either in the field or in the office.

A **linear referencing method** is a location referencing method in which a location is specified as occurring at some distance from a known point along a linear feature (for example, at some number of miles from the beginning of a roadway). A transportation agency usually (but not always) has one principal **linear referencing system**, which may include multiple linear referencing methods (different ways of specifying linear measures along roadways).
Linear referencing is but one type of location referencing, and the relationship to other types of location referencing (e.g., geographic coordinates) is essential to achieving full data integration. Therefore ‘LRS’ is used here for the more all encompassing ‘location referencing system’, while ‘linear LRS’ is used for ‘linear location referencing system’.

A node is the junction between two or more links, or an end point of a link. The term ‘link’ may have different definitions depending on context. A distinction is often made between a link in an abstract network model (a line segment with no shape points), and a link between two nodes in a GIS layer (which has the shape of the feature represented). This distinction is important in the context of data modeling. However, for this thesis the terms “node” and “link” will also refer to their common meaning for GIS data, in which they have two-dimensional (i.e., x,y) or three-dimensional (i.e., x,y,z) locations.

A traversal is made up of a set of links (or parts of links), in a defined order, and with a certain direction (see Figure 21). For example, a highway that begins at ‘zero’ at its southern end, with milepoints that increase throughout its length, is a traversal. A traversal is any uniquely identified path through a network for which a linear measure (e.g., a milepoint) can be determined at any point along the path. The more familiar but ambiguous term ‘route’ is best avoided, and used herein only where the context is clear (e.g., ‘U.S. Route 1’). A traversal may correspond to a named street, a bus route, a train line, or even a single path that includes travel by both car and train. A single link may be a traversal, as in a link-node linear referencing method (described below). A traversal does not have to be contiguous, but may have spatial gaps. Likewise, the measures along a traversal may be discontinuous, as is the case where mileage equations are used (described in section 5.5). "Polyline" is another name for a traversal.

Figure 21 Nodes, Links and Traversals

A milepoint is one type of linear measure. It usually measures the distance in miles from the beginning of a traversal (which does not have to start at zero). The term ‘milepoint’ is often used in this thesis for convenience, where kilometer point would serve just as well. The term log mile has been used by many transportation agencies to refer to milepoints, due to the practice of recording milepoint locations along roadways in a ‘log’ book.

An offset is a distance along a traversal from a point with a known linear measure. The offset may be from the beginning of the traversal (e.g., a milepoint) or from a reference point (such as an intersection or signpost) at some point along the traversal. A distinction may be made between
the reference point representing a physical object, and a traversal reference point that exists only as a location on a traversal corresponding to the reference point. The term ‘control point’ is often used synonymously with reference point, but sometimes is restricted to mean a point at a node with a known measure along a given traversal, used to calibrate the traversal’s measures.

A reference post is a physical sign or marker that displays either the linear measure for its location or a code for which the associated linear measure can be looked up. Mileposts and kilometer posts are reference posts that display their respective units of measure.

The terms section and segment have often been used rather ambiguously. Unless otherwise specifically defined, they both refer to a continuous length of roadway on one or more links (or portions of links). However, control section is often used to describe a section of roadway, with well-defined end points and a known length. Control sections may be established based on consistent linear attributes (pavement type, number of lanes, etc.), but this is not required. In some linear referencing methods, ‘control sections’ are established with associated linear measures, and are thus used as traversals.

An event is any feature, characteristic or occurrence along a traversal, such as a bridge, pavement condition or crash. A point event is located at a single linear measure, whereas a linear event has length, with location specified by a begin measure and an end measure.

Static and Dynamic Segmentation are defined in a later section of this chapter.

An anchor point is a location that can be uniquely identified in the real world such that its position can be recovered in the field (e.g., “the intersection of Oak and Maple Streets”). An anchor section is a continuous linear feature connecting two anchor points. Anchor sections have a direction specified by a ‘from’ anchor point and a ‘to’ anchor point, and have a ‘distance’ attribute which is the length of the anchor section measured on the ground. Professor Joseph Ferreira coined the terms anchor point and anchor section. They became the theoretical foundation of the effort to develop a generic data model for linear referencing (Vonderohe, et al, 1997). More complete definitions are provided in the Glossary (Appendix A), and the generic data model is further described in section 5.2.

4.2.2 Linear Referencing Methods

A linear referencing method provides a means for specifying locations along a linear network. Four elements common to all linear reference methods are:

1. Identification of a traversal
2. Identification of a known point on the traversal
3. Specification of a distance from the known point (an offset), and

There are two standard approaches by which these elements are employed. These are the:

1. The base-offset method, and
2. The reference point method

The base-offset method (see Figure 22) involves measurement along a roadway determined from a single base point at the beginning of the traversal, with an offset that may be an absolute or
interpolated distance. Where milepoints are used, the base-offset method is sometimes called a route-milepoint method.

**Engineering stationing**, used most by Engineers and Surveyors, is a base-offset method in which, typically, the base point is a surveyed location and offsets are measured along a surveyed base line in feet. This method may be very precise, although the base line usually cannot be determined in the field without a survey.

**Figure 22 Base-offset Linear Referencing Method**

The second approach, the **reference point method**, utilizes a series of reference points along the road (see Figure 23). Measurement is made relative to these points, which are typically located at intersections, bridges (center or end points), railroad crossings or other local landmarks. One variation of the reference point method is the **intersection-offset** method, in which an intersection is typically specified by naming the crossroads (this must be unambiguous). The identification of the traversal along which the offset is measured may be by road name and direction (north, east, etc.), or simply by direction, but this again must be unambiguous.

**Figure 23 Reference Point Linear Referencing Method**
**Address geocoding** is the process of coding street address ranges along the roadway network and enabling the display of individual addresses as interpolated along the links of the network. Address geocoding is accomplished in GIS in a manner similar to dynamic segmentation, however address ranges are typically coded for each side of each individual link. The GIS uses interpolation along links to determine the locations of addresses. If the intervals between addresses are not proportional to their distances along a link, inaccurate positions may be derived. Although this situation is not necessarily desirable, it is easily implemented and satisfactory for many less demanding applications.

Note that linear referencing methods and systems are completely independent from GIS, and were widely used well before the advent of the transistor. In linear referencing, locations are specified by a one-dimensional measure (an offset) along a linear feature (a traversal). In GIS, location is specified by two (x,y) or three (x,y,z) dimensions in a coordinate system (which can be changed in the fly). The integration of linear referencing with GIS is currently the principal method for integrating linearly referenced data with data located by other methods (e.g., GPS), however the distinction is important to keep in mind.

Linear referencing methods are put into practice by two general methods:

1. **Sign-oriented methods** involve placement of physical signs along roadways. There are two subcategories:
   
   (a) *The milepost method* employs signs that indicate the actual or approximate milepoints of locations from some zero reference point, the beginning of the traversal, usually at the beginning of the roadway, or at a state or county boundary.

   (b) *The reference post method*, in which the signs themselves do not necessarily indicate known distance from a fixed point. The signs may be placed at a variety of recognizable features (e.g., intersections, jurisdictional boundaries) or at some fixed interval. Central office records are used to equate unique reference post IDs (which do not necessarily follow any logical sequencing) with actual mileages.

2. **Document-oriented methods** avoid the costs of installing and maintaining signs in the field. The first type of document-oriented method uses a log, strip map, or other diagram (straight-line diagrams, or SLDs, is a pertinent example) to associate identifiable roadway features with their milepoint or reference point numbers. Another method employs street maps to locate incidents or attributes on the roadway system.

Many DOTs use a single or principal LRM. Other LRMs that might be of interest include for example:

1. Intersection/offset (intersections specified by their intersecting roads)
2. Reference point (potentially using the nodes as reference points from which offsets are measured)
3. Link/begin x,y/end x,y (event begin and end points are specified as Cartesian coordinates, e.g., as collected by GPS)
4. Non-LRS traversals (for example, transit and snow plow traversals)
It should be clear that whatever method is employed, the \textit{measurement of distance from a base point or reference point} is the basis for all linear referencing.

\textbf{4.2.3 Traversal Organization Schemes}

It is difficult to describe generically how traversals may be organized. This is because there are so many variations in how this can be done (as evidenced in the case studies). Three traversal organization schemes, or variations thereof, are employed by most transportation agencies (adapted from Nyerges, 1990). These are:

1. A named route
2. A link-node or link-offset
3. Control section.

They are described in a little more detail below.

1. A \textbf{named route} scheme employs a road naming convention (as a standard procedure for assigning names to highways and streets) and linear offsets (e.g., milepoints) from the beginning of each named route (see Figure 24, below). Each named route is a traversal. One common variation of this methodology, used by many state Departments of Transportation, breaks routes having a common posted name into separate traversals for each county or maintenance division.

\textbf{Figure 24 Named Route Organization Scheme}
2. A link-node or link-offset scheme specifies attribute locations along each link of the roadway system. A separate traversal is defined for each link (see Figure 25). The link identifiers are often derived from the node identifiers, hence the name ‘A-node, B-node’ is sometimes used for this scheme.

Figure 25 Link - Node Traversal Organization Scheme

3. A control section scheme establishes a “middle ground” approach between the route-milepoint and link-node schemes. A control section method breaks roadways (usually within a named roadway) into sections that are generally shorter than numbered/named highways (complete ‘routes’), but longer than single links. A traversal is defined for each control section. The control sections may be defined based on subsections of a named roadway, or based on having consistent physical characteristics, or by some other ubiquitous criteria (see Figure 26). Control sections may also be defined by standard (or nearly equal) lengths (see Figure 27). (The term ‘control section’ is sometimes used to describe a roadway section with homogeneous attribute data throughout its length, but that constraint is not assumed in this thesis).

Figure 26 Control Section Traversal Organization Scheme - by Major Intersection
Measurement along a traversal is made from either a control point or a reference point. In a GIS the distinction is important. A control point is a point at a node on the network with a known position in the GIS (with x,y or x,y,z coordinates). A reference point may not be at a node, thus measurement from a reference point is more problematic and imprecise in a GIS. In order to measure accurately from a reference point along a traversal, an artificial node may be required, thus creating topological divisions. Problems arise in both measurement systems when the roadway geometry is changed, such as when a road is realigned (e.g., “straightened”).

4.2.4 Linear Referencing Control and Event Data

Generally speaking, there are two types of data associated with linear referencing. These are:

1. Control tables, and
2. Event tables.

Control tables (or files) are essential to the internal functioning of the linear LRS. Depending on the LRS design, control tables may define and record traversals, reference points, control points, the relationship between internal traversals and milepoints along numbered/named highways (where they differ), mileage equations, and the correspondence between different linear LRMs.

Event tables on the other hand contain the attribute data for the linear objects being modeled, including both point and linear events (specified by offsets along traversals). Through relational constructs, event tables may be maintained completely separately from the linear LRS and linked only when needed (for display or analysis).

The use of events tables was demonstrated above with the development of Dynamic Segmentation, above.

The type of LRS user, whether experienced technician or peripheral operator, must be considered when designing interfaces or entire systems. Transportation data is expensive to collect and
maintain, but its true value is typically proportional to how easy it is to access and utilize. Key issues include:

1. Will data be kept on-line or off-line?
2. What event tables will be maintained in the same system as the control tables?
3. When traversals are updated (e.g., due to realignments or re-measurements), are historical event data locations rectified to reflect these changes? Or, are the historical location references maintained relative to the now obsolete network, perhaps enabling reconstruction the traversal network at any historical time?
4. How will ‘external’ databases that rely on linearly referenced locations, but which are managed separately from the LRS control tables, be kept synchronized with updates to the LRS?

As an example, Idaho’s linear LRS maintains active and inactive dates for each traversal in their system throughout its 20-year history and can thus rebuild the traversal structure for any time period. Historical records such as accidents are always referenced back to the network that was valid at the time the event occurred. In contrast, PennDOT keeps only current traversal information in its control files, and re-calibrates all historical event information following any traversal updates.

4.2.5 The Coding of Ramps

A ramp is defined in Table I and the Glossary as a, “connecting roadway between a freeway or expressway and another highway, road or roadside area”. Several alternatives exist for the coding of ramps in the field and are briefly exemplified here. As outlined indicated in Figure 28, the generic options for encoding ramps are:

1. Part of an adjoining route (and a schema needs to be set in place for this, as exemplified in the Figure)
2. At the end of a route (and similarly a scheme has to be in place to select the ramp).
3. A separate ramp file.

A ramp numbering scheme also needs to be set in place. This may be done by for example:

1. Clock-oriented methods
2. Route-oriented methods
3. Other schemes, such as random numbering

Variants of all these schemes are found in the field with different DOTs. Chapter/section 6.5.2 reviews the set-up of ramps in the context of the selected DOT case studies.

Ramps exemplify how one single highway network piece may be setup and coded in many different ways. This may not argued to be a significant issue if for example a single state DOT picks a single method. However, even within one state different methods may be in use, and there may be a data conversion issue if for example data is being reported to third parties (such as in the context of Highway Performance Measurement Systems data, HPMS, that is reported annually to the FHWA. There is thus at least some case for establishing if not one “better” method, at least a set of better and intercommunicating methods. These can then potentially become objects that can be more likely supported by data transfer standards and COTS software.
Route Definition: Ramps Option I
- Ramps appear as part of higher numbered route

Ramp Numbering: Option I
- Start (say) north-east corner, go (say) clock-wise (e.g. 1, 2, 3, 4)

Route Definition: Ramps Option II
- Ramps appear in separate ramp file, attached by both routes

Ramp Numbering: Option II
- Number from (say) the higher numbered route.
  - Procedure
    - North-West
    - North-East
    - South-West
    - South-East

Route Definition: Ramps Option III
- Ramps are stored in the higher numbered route as it appears at the end of the route

Figure 28 Ramp Encoding Schemas
4.3 GIS Methods and LRS Methods

Linear referencing methods (as a spatial scheme for organizing linear transportation data) and GIS-T methods and technology (as a means of displaying it) are exceptionally powerful tools. They form the nucleus of most state-of-the-art transportation management systems or ITIS.

GIS, with the extensions of dynamic segmentation (see Chapter/section 4.4), provides a powerful tool for the analysis and display of linearly referenced data. Traversal systems can be generated by semi-automated means, built on top of the links of the GIS road network. Prior to dynamic segmentation, the wealth of information stored in event tables was displayed primarily on straight-line diagrams, in printed log listings, or on manually generated maps by time-consuming processes. The ability to visualize the wealth of data stored in one or more event tables is what first made GIS such a desirable tool for transportation planning and analysis. Subsequently, GIS has been used not just for visualization, but also increasingly for spatial analyses involving linearly referenced data.

At first look, the integration of the two, a method and a technology, appears a well-fitted match. However, some fundamental incompatibilities have emerged. In fact, these incompatibilities have motivated in part research efforts such as the NCHRP Project 20-27(2) generic linear referencing data model and the Dueker-Butler enterprise model (described in Chapter 2).

This is not to say GIS and linear referencing cannot complement each other. They can be made to work very well together and new innovations promise greater utility to transportation agencies. Nevertheless, incompatibilities between the two must be fully understood. Clearly the technology that was designed to implement LRS methods did not fully reflect the richness of the spatial content. Understanding the richness of the spatial domain and the limitations of simple models is an underlying theme throughout this thesis.

This section here attempts to practically demonstrate such issues. The four case studies are used as guiding examples.

4.3.1 The Difference Between Linear and Geodetic Referencing

In summary to date, linear referencing lays out roadway events (and event end points) like “knots along a string”. Developing DOT business area management tools from linear referencing schemes should in theory generally for most part be an intuitive process. A map is highly advantageous for the display and interpretation of results, but is not an absolute requirement. Linear referencing is a one-dimensional representation of a reasonably one-dimensional feature—for example, a road. All that matters is the traversal name, reference point, offset(s) and the event.

One area where the simple paradigm gets tested is as one moves into off-the-shelf technology. There are limitations to the accuracy of linear referencing as it is typically implemented in a GIS environment. These limitations are due to the fact that linear referencing is one-dimensional (offset along a traversal), whereas topographic information is three-dimensional (x,y,z). GIS as a technology is still primarily today primarily geared to two-dimensional data storage and analysis. This raises issues regarding the hills and valleys a road passes through, and relating linear
locations to the rest of the world, that is, the true travel distance along a road compared to its flatland distance.

This lack of topographic referencing is in reality not generally a so serious a concern as it might be, for two principal reasons:

1. **3D Error Small:** In most states and certainly the less mountainous the error introduced by the third dimension is actually quite small and certainly within the bounds of measurement that at least traditionally had been used until recent times.

2. **Incorporate 3D Effect:** Linear referencing was not primarily designed for the purpose of directly incorporating 3D. However, if the linear measures of reference points have been determined by an accurate distance-measuring instrument (DMI), then these measures will have incorporated the roadway’s three-dimensional shape. However, this type of three-dimensional topographical information does not usually exist within a GIS road network data layer.

In contrast to linear referencing, GIS can store geodetic information because all GIS software is capable of at least two-dimensional referencing (x,y). There are some problems however.

Looking at Figure 29, three views of the same road are illustrated. In the ‘linear view’ of the 1.2 mile long road, five events have been located using a DMI. We know the road is 1.2 miles long because the DMI measured this distance. The only thing we do not know is the path of the road relative to the rest of the world. The GIS view offers the “bird’s-eye” roadway with twists and turns, the benefit of the second dimension. What is missing now is an appreciation of how long the road really is. Any DMI measure of distance up and down hills is lost as it is impressed (or projected) onto the flat GIS coordinate space, so when the GIS measures the road length, it only comes up with 1.1 miles. The roadway “zigzag” is visible but the true distance along the path is lost. A cut and fill CAD profile view would be able to recapture the true DMI distance because the third dimension is fully represented at each point along the roadway line.

**Figure 29 GIS Distance Lost to Changing Elevation**

<table>
<thead>
<tr>
<th>Linear View</th>
<th>0.0</th>
<th>0.2</th>
<th>0.3</th>
<th>0.5</th>
<th>0.6</th>
<th>0.8</th>
<th>1.2 DMI miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>GIS Top View</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.1 flat miles</td>
</tr>
<tr>
<td>CAD Profile View</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>1.2 CAD miles</td>
</tr>
</tbody>
</table>

Practically speaking, transportation length measures are not widely affected by this problem. For example, a 10% slope, the difference between horizontal and surface distance is just 0.5%.
Except for in exceptionally steep terrain, the error is probably less than the error found in the original DMI measure. A greater source of error is typically due to GIS link lengths that have been substantially generalized from the true roadway alignment, as is the case for 1:100,000 scale data. Length measures based on DMI measures will typically be longer than “flatland” measures.

There are other difficulties concerning linear and geodetic measures. For example, take a patrol car making an accident report. Using non-differential GPS the accident may be located to no better than 300 feet. Let us assume the officer also has time on his hands and performs skillful surveys of the accident’s location to within 1 inch. Both these measures are absolute positions, and because linear referencing is a relative positioning technique, data integration is difficult. USGS 1:24,000 scale maps are accurate to about 40 feet, and so whatever accident coordinate we plot (300 ft or 1 inch accuracy), the chances the accident is going to appear on the roadbed are slim. All these issues come to play when linear and geodetic referencing is considered. Current practice in integrating these different types of measures has had limited success, given the limited accuracy of most digital base maps, yet it is adequate for many tasks. The need for greater accuracy could change, for example, when ITS-enabled vehicles require positioning accuracy at the lane-level, and thus research continues in this area.

4.3.2 Implementing Traversals in GIS: Coding and Calibration

So what does this all mean? First let’s consider how linear referencing is linked to GIS. The simplest technique is to define a traversal as a collection of GIS links, then associate ‘begin’ and ‘end’ measures with each node along the traversal as determined by the lengths of the GIS links. Differences between the GIS and DMI lengths are inevitable and tend to be greater the longer the traversal, as reflected in Figure 30 below. For the figure below, a crash that occurred at milepoint 6.3 would not appear in the GIS data – it would have ‘floated’ right off the traversal.

**Figure 30 Comparison of DMI and GIS Measures**

<table>
<thead>
<tr>
<th>DMI measures: 0.0</th>
<th>3.2</th>
<th>4.6</th>
<th>6.5 miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Default GIS measures: 0.0</td>
<td>3.1</td>
<td>4.5</td>
<td>6.1 miles</td>
</tr>
</tbody>
</table>

*Total lengths differ ... where is the crash recorded at milepoint 6.3?*

A more accurate implementation of the linear measures occurs if one calibrates the entire GIS traversals to their known DMI mileages. Most GIS packages that support dynamic segmentation can do this automatically once the DMI measures are associated with the traversals. In the example of the figure above, the calibration would be from 0.0 at the first node to 6.5 at the last node, with linear interpolation between the two. As indicated in Figure 31 below, although the full length now agrees with the DMI length, the interpolated intermediate measures still differ from the DMI measures.

To a large degree, this level of calibration provides suitable, basic functionality. The crash at milepoint 6.3 will now be displayed in the GIS. However, the more the GIS link distances differ from the DMI distances used by the linear LRS, the more any stationary events will tend to ‘float’
up and down the GIS roadway graphic. This is particularly problematic if the traversal lengths are re-measured and updated between inspection cycles, as events will float to new locations following every update. (This is a common complaint in the DOTs). Most DMI measures are considered good to 1/100th of a mile (50 feet per mile). At this level of accuracy, event floating may be amusing, but functionally is not necessarily a problem.

**Figure 31 Comparison of DMI and Calibrated Traversal Measures**

<table>
<thead>
<tr>
<th>DMI measures:</th>
<th>0.0</th>
<th>3.2</th>
<th>4.6</th>
<th>6.5 miles</th>
</tr>
</thead>
<tbody>
<tr>
<td>Calibrated GIS traversal measures:</td>
<td>0.0</td>
<td>3.3</td>
<td>4.8</td>
<td>6.5 miles</td>
</tr>
</tbody>
</table>

Measures at intermediate points differ ... total lengths agree

The degree to which events float from their true locations depends mainly on the accuracy of the GIS link lengths. Floating may be greater for longer traversals, but calibration to the traversal level will mitigate this factor. Another factor is the fidelity with which the traversals have been (or can be) coded in the GIS data. For example, the GIS data may include detailed interstate interchanges with all ramps represented, whereas a legacy LRS may define a single traversal for divided highways that conceptually meet at a single point, see Figure 32. The traversals may include reference points where they intersect, but it is not clear where the corresponding node should be in the GIS data. Situations like this one have motivated the refinement of legacy LRSs, or at a minimum the adoption of separate traversals for opposing travel directions on divided highways.

**Figure 32 Interstate Interchange with Single Traversals for Divided Highways**

Where should the 'traversal' node be located in the GIS data?

The next level of calibration is to establish control points at intermediate nodes along each traversal, so that measures are calibrated between each pair of successive control points. This is
generally a labor-intensive task. A common practice is to establish calibration points only at major intersections and perhaps other suitable reference points (e.g., bridges and railroad crossings), at perhaps with some maximum separation. The density of control points can be increased up to the point where accuracy needs are met. Of course, the LRS must include accurate, stable measures to be used for the control points, which is not always the case. This level of calibration is likely to meet nearly all-practical transportation agency data analysis needs.

One method of increasing accuracy in event locations displayed in GIS is to use a reference point method (supported by some GIS software). In this case, an event is located by an offset along a traversal from a reference point (see Figure 33, below; see also section 4.2.2). In the GIS, each reference point is coded with its unique identifier. The lengths of the GIS links making up the traversal must also be calibrated to real-world lengths in the correct units. Generally, this is done by coding each reference point with its known measure along the traversal, and using it as a control point for calibration. Alternatively, entire traversals are only calibrated to their known lengths, and the reference points are only coded with their identifiers. In either case, there is less of a tendency for event locations to float, for even if the measures along a traversal are updated, the offsets from the reference points remain the same.

Figure 33 Crashes Located by the Reference Point Method in GIS

Another method for minimizing the degree to which event locations float (and the need for calibration) is to establish relatively short control sections, each of which is a separate traversal. The PennDOT LRS, with control sections of approximately 0.5 miles each, has this approach. Of course, calibration to a maximum distance between control points will accomplish the same purpose. (Another advantage of control sections is that fewer events need to have their locations updated when a control section is updated.)

Although not needed for the vast majority of transportation applications, even greater precision in traversal calibration can be obtained with higher-end GIS software that supports three-dimensional coordinates and calibration by 'true' one-dimensional surface length. An alternative is to associate the true surface length with each GIS link (which can be done in some GIS software by overlaying the road network layer on a digital elevation model of suitable accuracy), then to use the true surface lengths as weighting factors in the calibration between control points.
Most GIS software packages that support dynamic segmentation contain a suite of calibration tools. They tend to be imperfect in action, and may require substantial manual input and manipulation, but for the most part they are adequate for the job. If not provided by the software tools, further calibration can usually be obtained with additional custom quality control measures or manual checking.

4.3.3 Integrating Linearly Referenced Data

A potential major challenge for managing transportation data and forming Integrated transportation Information Systems (ITIS) is the integration of linearly referenced data from different sources, and stored by different linear referencing methods.

Many state DOTs have managed over the years to set up multiple linear referencing systems within the same agency. This has often been because state DOT’s have been organizationally a set of autonomous activity areas, e.g., bridge, safety, highways, etc. These areas set up their own “data islands”. Practically speaking, the integration of data based on different linear referencing systems has not been problematic until recent years. The FHWA two-day workshop on ITIS demonstrated that historically data sharing between divisions or institutions was relatively rare. However, the information management climate has changed. This is because in short:

1. New information exchange techniques have simplified the information sharing process
2. Advanced applications like intelligent transportation systems (ITS) are demanding greater integration.
3. The ISTEA legislation demanded it.
4. In a wider sense, the general public has begin to expect that information be integrated.

There are four principal ways to minimize sharing difficulties or to otherwise bring disparate linear LRS measures together:

1. Adopt a common linear LRS datum, as suggested by the GIS-T Pooled Fund Study
2. Develop custom procedures and routines for each desired conversion
3. Maintain anchor points and data as closely as possible to geodetic reality
4. Develop a set of translation and data conflation tools to transcribe information between linear LRS and other spatial data structures.

The methods that will prove to be best for integrating different linearly referenced databases will remain under debate for some time. However, a closely related issue is the search for a standardized data exchange format. The Federal Geographic Data Committee (FGDC) is in the process of setting such standards, including linear LRS exchange formats. The ITS community is directly involved because ITS will simply not succeed without such standardized exchange formats. The European Geographic Data Format (GDF), another standard format for roadway data, has been adopted by many commercial providers of street centerline data and provides another method of data exchange. Although these standards are only briefly discussed in this manual, anyone entertaining the design of a spatial transportation database should be apprised of the state of standards development for transportation data.
4.4 Static and Dynamic Segmentation Methods and Technology

This section briefly reviews the principal highway data linear segmentation schemas used by DOTs.

4.4.1 Static Segmentation

Under static segmentation, a unique data record is maintained to store a set of attributes for a single highway segment of defined location and length. There are two principal sub-classes of static segments:

1. **Fixed-length segments**
2. **Variable-length segments**

**Fixed-length segments** are used by some transportation agencies. Highway routes are broken up into segments of an equal length small enough (e.g., 0.01 miles) so that they may be considered roughly homogeneous with respect to their attributes. Thus, it is a method of assigning attribute values to pre-defined segments along the linear network. With static segmentation in GIS, roadway attributes are therefore confined to complete links. If an attribute value varies along a pre-defined segment, an average value may be assigned. (See Figure 26). Some highway departments use static segments lengths of 0.1 mile. Static segmentation is the way the majority of highway departments have traditionally stored data. A major issue with static segmentation is data redundancy.

Taking the case of PennDOT, with 44,000 miles of road, this provides for 440,000 segments to maintain in the database. Highway departments will typically store 30 to 80 items of information (e.g., road width, type, quality, level of cracking, etc.) on their highway sections. In PennDOT’s case they store 80 items. This equates to approximately 35 million cells in a relational database table. This implied the use of mainframe computer systems. Many of the cell values would not change from row to row in the database – 176 is “interstate” in the interstate column in the database for 300 miles across Pennsylvania (or 3000 database rows). Printing out the “mounds of green paper” for many state DOT databases, it was very apparent to see the repetition that would exist across many columns for multiple pages.

Figure 34 exemplifies static or fixed length segmentation. For a 3.0 length of road, with 5 attributes, and 0.1-mile segments, there are 300 records and a total of 1500 database attribute cells.

Some states used a variation of static segmentation, **variable length segments**. This is where a new highway data maintenance segment was created when one of a number of key highway characteristics would change (for example, county boundary, pavement type – concrete/bituminous, etc.). The number of key attributes was typically kept to about 5 to 8 (e.g., Delaware uses 6), which is redefined on the route whenever at least one of a selected set of highway attributes changes in value. The actual number of segments for a given stretch of roadway depends on the attributes contained in the table and how often each such attribute changes in value.
4.4.2 Dynamic Segmentation:

Static and variable length segmentation assumes a pre-segmentation of the highway in database management terms. In contrast, **Dynamic segmentation** (DS) is a method of locating events along the traversals of a linear network with no previous physical segmentation of the network (Dueker and Vrana, 1992). The term is generally (but not always) associated with the application of linear referencing in GIS. With dynamic segmentation, linear events can begin and end at any points along a given traversal, and are not restricted to whole links. Figure 35 demonstrates the operation of DS.

In the Figure 35, it can be seen for the same 3.0 mile length of highway, data has been collected on 5 attributes (i.e., road width, condition, class, accident, and surface). Some data items, as befitting their use or data collection may be available in a more disaggregate (e.g., here highway condition, perhaps collected down to 1/100 or 1/1000 mile) or less disaggregate form (e.g., surface type, here perhaps only available in 1/10 mile sample measures). Thus, the attribute tables may be short (no or little data) or log, depending on the amount of data collected, available or necessary for the functional use and area. For the particular dataset above there are a total 17 fields of data stored and collected. This represents a significant saving over the static segmentation approach above where there were 1500 attribute cells stored.
In the example in Figure 36, Dynamic Segmentation is used to conduct an on-the-fly analysis of a linear spatial query. Here the software functionality generates a result set from a defined query. The result query may be further queried to produce a further result sub-set.

Dynamic segmentation is a method of locating events along the traversals of a linear network with no previous segmentation of the network. The term is generally (but not always) associated with the application of linear referencing in GIS. In its essence, this technique uses measured offsets from fixed and known reference points to place attribute features on roadways (the essence of linear LRS). This method does not create new topological divisions (i.e., nodes) in the road network; linear events can begin and end at any points along a given traversal. Dynamic segmentation may be considered an “engine” to implement one or more linear reference schemes on a network representation.

A key advantage of dynamic segmentation is that it enables visual network overlay of attribute data to be performed “on the fly” by linking the GIS data to event tables stored in an RDBMS. Note that this is a visual overlay; overlays for query and reporting in tabular format are more complicated (discussed in section 4.5.3). This dynamic overlay also avoids the need to store the larger; more difficult-to-maintain, attribute tables associated with a fixed, or static, segmentation of the roadway. All dynamic segmentation really does implement a linear referencing method along GIS links, and other than event “floating” due to inadequate calibration, it is the perfect tool to combine linear referencing and GIS functionality.

In general, dynamic segmentation is a more compact way of storing transportation data. It removes data redundancy. In the PennDOT case described earlier, in the section on the use of Static Segmentation (Chapter/section 4.4.1) use of DS was potentially able to reduce the size of the datasets by a factor of 5 to 10.
### Figure 36 Dynamic Segmentation: Example

Step 4: Software performs intersection between tables

"Show me the section of roadway where: road condition = A or surface type = A2"

Selected records where COND = A or ST = A2

<table>
<thead>
<tr>
<th>From</th>
<th>To</th>
<th>Cond</th>
<th>ST</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.2</td>
<td>A</td>
<td>C1</td>
</tr>
<tr>
<td>0.7</td>
<td>0.6</td>
<td>A</td>
<td>C1</td>
</tr>
<tr>
<td>1.4</td>
<td>1.7</td>
<td>C</td>
<td>A2</td>
</tr>
<tr>
<td>2.5</td>
<td>3</td>
<td>A</td>
<td>A1</td>
</tr>
</tbody>
</table>
Many agencies have employed this DS to the gain the benefits of COTS linear referencing. However, some state DOTs continue to employ static segmentation with success. Static segmentation can also be useful in a data warehouse environment. As discussed in section 4.5.3, the data structures of dynamic segmentation may hinder the ability to perform ad hoc queries of multiple event tables.

Based on the wider desk exercise carried out here, and the Case Studies reviewed in Chapters 6 and 7, consideration was given to what Dynamic Segmentation features that are key to field use. The following in summary lists appropriate features:

**Data structures:**

1. Route system, route, node, linear event and point event data structures
2. Flexible user input to routes, node, linear event and point event attributes
3. Allow for overlapping (looping) and discontinuous routes
4. Allow for divided routes (two parallel arcs in the same route)
5. Allow for shared routes (single arc shared by two different routes)
6. Allow for multiple route names
7. Maintain Network topology for performing routing algorithms on routes
8. Allow for representing transit topology (transfer penalty, connections, etc.).

**Tools:**

1. Read and write directly to route attribute files stored in external databases
2. Build routes automatically from arc route identification attributes
3. Calibrate map route distances to observed route distances
4. Overlay and dissolve routes in order to build new route attribute tables
5. Establish location of a point or linear event as an offset to a node, to a route or arc beginning, midpoint or end, or to another event
6. Route connectivity and directionality checking tools
7. Tools for querying multiple attributes with different features (point on arc events, or arc on arc events)
8. Tools for on-the-fly display of multiple attribute queries

**Display:**

1. Good display (screen generation) performance
2. Display strip maps of routes, node, linear event and point event attributes
3. Full route symbology, hatching, and text placement capabilities
4. Flexible route manipulation GUI

Current COTS does not fully meet this specification.

**4.4.3 Inconsistencies Between Linear Referencing and Network Representation**

Some inconsistencies between linear referencing and network representations were introduced above, in cases where linear measures differ from computer measurement of the GIS line graphic. Generic data models for linear referencing are attempting to accommodate this problem through the use of anchor points and anchor sections (see section 5.2). Rather than using GIS nodes to
begin and end traversals, use of known real-world positions (i.e., anchor points) has been suggested: intersections, bridges, etc. Anchor sections would connect anchor points and contain the DMI or real world distance — rather than the GIS determined line length. Dueker and Butler are also developing a model where linear LRS events may locate on more than one transportation feature (see Chapter/section 5.4). For example, if an accident occurs at an intersection of two roads between a trolley and a bicycle path, which traversal will carry the accident? Transit route, bike route, Main Street, or Elm? At the present time, most of these issues may only be accounted for through the use of established standard operating procedures.

The wider topic of reconciling the network base and the LRS is fundamental to LRS. It will be further addressed in later chapters.

4.4.4 Conflation

One solution to the disparate data integration problem is a process called “conflation”. Consider two GIS network layers (e.g., road centerline coverages) that overlay, but do not match up (or spatially coincide). Conflation is the process of physically combining two GIS networks and their respective attributes. The process is often limited to transferring attributes from one network to the other (typically, the network with the better spatial accuracy). However, the process may allow user-selected criteria to guide the action of merging the networks. Most often, the process is decision-intensive and requires manual supervision. In GIS networks that include traversals, the traversals and their associated information may also be combined or transferred. Conflation can therefore be used to integrate two or more linear referencing methods.

Unfortunately, once a data set has been conflated to a more accurate base map, other maps may no longer fit correctly. For example, take roadway and surface waters data developed at the same time from the same source, say USGS 1:24,000 scale maps. On the maps, bridges span streams and rivers in their ‘correct’ locations. Let’s say this particular state DOT had recently developed a GIS roadway network accurate to 5 meters through the use of a GPS receiver (e.g., LANDGPS) mounted to their DMI van. Once attribute data from the old USGS 1:24,000 maps have been conflated to the more accurate GPS base, the bridge structures will shift away from the streams and rivers (the “bridge over the river” problem). The road base accuracy has improved while the accuracy of previously developed overlay information has not.

In parallel research to this thesis, the author earlier was involved in initiating and conceptualizing the technical basis and approach for a 3-year or so effort into creating network conflation tools, supposedly first coining the phrase. These tools worked in short by conducting principally an extensive set of topological, geometric and name-based comparisons. The very extensive toolbox required to undertake this task had always to be modified and calibrated for every major city network pairs on which it was applied, as it was found that there were always unique detailed elements in every local situation (e.g., in Los Angeles, the Thomas Brothers and ETAK supplied networks, and similar network pairs in Washington, Detroit, Boston, Paris, etc.). The setup of these tools practically exemplified the real world range of “messiness” of spatial data briefly referred to in Chapter/Section 3.2.1.

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7 The theoretical base to support this work was attempt #1 at original thesis practitioner research. However, the tools and approach have now entered the commercial domain in 1996, with Microsoft purchasing a copy to help create the COTS MapPoint product. The basis for this current work started in fuller swing at that time.
4.5 Other Relevant Field Technologies and Applications for LRS

The subject should also be considered with the “enabling technologies”.

The number of tools available to assist linear referencing practitioners is large and growing. Some are indeed revolutionary. The mainstay technology for many LRSs in the field remains the videolog van fitted with a distance-measuring instrument for inventory assessment and archiving. Straight Line Diagrams (SLDs) work well with video logs; however, improving computer capabilities are rapidly displacing the SLD for dynamic map displays. Many states are mounting differential GPS units on their video vans, and building entirely new high-accuracy base maps at very low cost relative to other information operations.

New technologies applicable to LRS that are reviewed here are:

1. GPS
2. Videologging
3. Data Warehousing

Other technologies that are also increasingly relevant to LRS include:

4. Laser Swathe Mapping
5. Aerial photogrammetry, and
6. Satellite imagery (particularly now that 1 meter resolution imagery is becoming readily available)

GPS locates points with absolute coordinates of latitude and longitude, while linearly referenced measures are relative to points of known measure along predefined traversals. GIS has enabled the integration of geographic coordinates with linear measures. Linking and calibrating different linear referencing methods through geographic coordinates is a powerful tool, and is a current area of research within the Intelligent Transportation Systems (ITS) community. Development of standards for spatial data transfer is also addressing translations between referencing systems.

4.5.1 Global Positioning System (GPS)

GPS has been proposed as an alternative to LRS. The section below briefly reviews the nature of the technology, accuracy considerations, its relevance to LRS, and the relative advantages of LRS and GPS.

4.5.1.1 What is GPS?

The Global Positioning System, or GPS, is satellite-based global location system. GPS is a US Department of Defense (DOD) owned and operated radio navigation and positioning system. This $10 billion joint-service program began in 1972 following the integration of the US Navy and US Air Force radio navigation systems. GPS became fully operational on December 8, 1993 when the 24th functional satellite completed the planned constellation.

In essence, GPS receivers can provide the precise location of a point on the ground in terms of \(x, y, z\) coordinates (e.g., latitude, longitude and elevation with respect to a specific geodetic datum).
Various accuracies can be attained, and sub-meter accuracy is now attainable on a regular basis. Until recently it could only in real time provide accuracies of within 10 or 20 meters GPS – that is, it provided a method for collecting geographic coordinates to an accuracy of several paces on the ground or better. However, it has recently been announced (May 2000) that it will be operated in its more accurate form (with selective availability, S/A, switched off), with accuracies in real time close to 1 meter.

The author of this thesis was responsible for a project that over 5 years took a GPS-equipped van for demonstration purposes to over 30 state DOT's. He may thus have indirectly further propagated the relevance and use of traversal-based measures and storage.

4.5.1.2 Accuracy Considerations

Some detailed information on the GPS is provided below to highlight the importance of newly attainable accuracies to linear and location referencing.

GPS ascertains ground position by first timing a radio signal from the satellite to the receiver to determine the line-of-sight distance between the two. Coupled to this timing signal is the estimated location of the transmitting satellite's stable position relative to the earth's center. A simple vector subtraction then yields the receiver's absolute position. Signals from four satellites are needed for a four-dimensional fix (latitude, longitude, elevation, and broadcast time).

Because the original use of GPS signals was for defense purposes, they are encrypted with the simple intent to prevent others from mimicking the signal. The military is not particularly troubled that there are a variety of techniques on the market that quickly and easily break through the encryption (e.g., cross-correlation and z-tracking techniques). The only true hindrance to civil GPS use is thus selective availability, which is the intentional degradation of a signal correction factor. When active, this limits civil use to no better than 100 meter accuracy. This degraded accuracy can be improved by comparing received GPS signals with the same received signals at a known point. An error difference is generated by subtracting the satellite's positional estimate from known position, hence the name differential GPS (DGPS). There are three forms of DGPS: Local Area Networks (1-10 meter accuracy), Wide Area Networks (0.5 meter), and baseline interferometry (sub-centimeter accuracy).

Wide Area Networks (WADGPS) are a new operating concept that will revolutionize the GPS usage, as 0.5 m accuracy without linkage to a base station will become the norm. Every state DOT should thoroughly research this technology before making GPS or data logger purchases of any type. Baseline interferometry is primarily used for survey applications. Position is not determined strictly by satellite distance determination, but rather through the statistical determination of the number of carrier wavelengths between the base and rover.

It is common to compare the thickness of a map line with its scale size across the earth's surface. Even at a scale of 1:2400, a drawn line would still be 4 feet thick on the earth's surface. When significant figures of angular measure are increased (see Table 21 Significant Figures, GPS Accuracy and Scale Map Thickness) a relationship between map scale and GPS accuracy may be illustrated. As WADGPS comes on-line, real-time accuracy to seven significant figures or 0.5 meters without fixed base stations will be commonplace. Databases built to accommodate GPS coordinates should be designed to carry these field widths.
### Table 21 Significant Figures, GPS Accuracy and Scale Map Thickness

<table>
<thead>
<tr>
<th>Lat/Long Stored Accuracy</th>
<th>Distance at Earth’s Surface</th>
<th>Approximate Map Accuracy Limit</th>
<th>GPS Accuracy Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>1°</td>
<td>100 (111) km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.01°</td>
<td>1 km</td>
<td></td>
<td></td>
</tr>
<tr>
<td>0.001°</td>
<td>100 m</td>
<td>1:250,000</td>
<td>S/A on - no differential</td>
</tr>
<tr>
<td>0.0003°</td>
<td>30 m</td>
<td>1:62,500</td>
<td>S/A off - no differential</td>
</tr>
<tr>
<td>0.0001°</td>
<td>10 m</td>
<td>1:24,000</td>
<td>LADGPS</td>
</tr>
<tr>
<td>0.000006°</td>
<td>0.6 m</td>
<td>1:1200</td>
<td>WADGPS</td>
</tr>
<tr>
<td>0.0000001°</td>
<td>1.0 cm</td>
<td>1:25</td>
<td>GPS Baseline Interferometry</td>
</tr>
</tbody>
</table>

#### 4.5.1.3 Relevance to LRS

The use of GPS is particularly relevant to linear referencing for a number of reasons. The accuracy and permanency of geographic coordinates is appealing, especially given the problem of ‘floating’ locations in some linear LRSs that lack adequate location controls. Data collection by GPS is becoming common, leading to new requirements for converting between linear references and geographic coordinates.

It has become economically feasible to greatly improve the accuracy of GIS road network base maps by GPS collection of roadway centerlines and other roadway features. There is extensive interest among transportation agencies to improve GIS road network accuracy to enable integration with design plans and other civil engineering data. Emerging technology now enables the more efficient storage and analysis of geographic coordinates in relational databases. Geographic coordinates may be stored in association with linear referencing measures to facilitate conversion between the two referencing methods.

GPS-equipped data collection vans are now used by many DOTs and each year significantly add to the volumes of recorded data available on highways. In a sense the use of the vans propagates the use of LRS as the vans linearly collect data (essentially on centerline or bi-directional track basis).

Figure 37 shows the overlay of GPS recorded centerline data with an aerial photograph. Unfortunately, this density of the aerial image with overlaid GPS recordings does not show well in black and white versions, but features can be seen on careful inspection. Examination shows that centerline data may be gained which closely maps to the aerial image. (Two North-south links in the center of the picture which are ‘grayed’ out, show vehicle tracks). In the bottom right corner of the picture are a number of black dots indicating locations where the vehicle lost satellite track. Most data recoding vans include the ability to switch to DMI traversal-measures for this purpose.
The reasons that data that is originally collected with the aid GPS may be reduced to traversal-form are an underpinning to the relevance of the work conducted here. They include in short:

1. Route Operation: The data are typically anyway being collected on a route basis as this is the way data maintenance activities have been institutionally set up. As many operational activities anyway occur on a route (for example, snow plowing) there is a rational operational basis for such operation.

2. Detector Operation: Some of the detection technology used on the highway data maintenance vans may only “fire” when there is a change of condition from one calibrated type to another.

3. GPS Operation: In reality for a number of reasons (e.g., position of satellites, canyon effect of buildings), the GPS signal may be lost and in any event is matched with that from a linear DMI.

4. Data Reduction: DOTs have expressed a user need to have the data reduced to linear “dynamic segmentation” linear form.

5. Calibration and Comparison: The reduction to linear form facilitates ready comparison to known measured offset landmarks and existing legacy data.

The original data recordings are usually kept in archive.

There is transition problem where one layer is improved by GPS before another, which is even of wider import than the within route calibration problem that occurs when within geometry is updated (as was briefly reviewed in Chapter/section 4.3.2). An enterprise-wide spatial database strategy is required to keep datasets in ‘logical sync’ (e.g., correct topological connections, adjacencies, etc.). the use of benchmarks of anchor points may also help facilitate the reconciliation process.

4.5.1.4 Relative Advantages of LRS and GPS

It has been argued that the high accuracy of GPS-based methods of roadway data collection, combined with the decreasing cost of data storage, will do away with the need for linear LRS methods (Bespalko, et al, 1998). However, this argument seems to neglect some of the advantages of linear referencing, which include:

1. Existing Legacy System: The advantages of linear referencing, such as its history of use, its appeal as a simple method for data collection and reporting


3. Technical Issues: There are also difficulties in using GPS for the collection of roadway attribute data – for example, the need for a stable, highly accurate base map and standardized methods of GPS data collection across the agency. These requirements are usually not met in state DOTs today.

4. Data Management And Reduction Issues: In addition, greater volumes of data must be collected, maintained, retrieved and analyzed, all of which involve greater costs.

The collection of roadway attributes that begin and end along commonly defined routes (or traversals) is a well established practice that enables different event data sets to be compared and integrated based on their locations.
Despite the fact GPS as a technology clearly works, work in DOTs to date has also shown that in short they have not institutionally learnt to use the technology. There are also difficulties in using GPS for the collection of roadway attribute data. These include for example:

1. The need for a stable, highly-accurate, commonly used and updated base map
2. The need for standardized methods of GPS data collection across the agency. These requirements are usually not met in state DOTs today.
3. In addition, while the costs of data storage are being lowered, greater volumes of data must be collected, maintained, retrieved, checked and analyzed, all of which involve greater costs.

GPS data collection certainly promises to greatly improve the accuracy of transportation data, but it seems likely that GPS will enhance the functions of linear referencing rather than replacing them.

GPS is actually used to help collect linear data. State DOT videolog vans are equipped with GPS units to gain an offset measure distance. These vans are equipped with gyroscopes for alternate linear distance measures for when the GPS signal track is lost. GPS data collection certainly promises to greatly improve the accuracy of transportation data, but it seems likely that at least in the immediate and middle term, GPS will enhance the functions of linear referencing rather than replacing them.

As noted in section 3.5.6, ITS makes considerable use of GPS technology. Microsoft and other companies have invested significantly in creating US national street files that they plan to use by 2002 with GPS for hand-held computer/ use for activities such as automated ordering of pizza (from couch or car) on demand. The national standards to do this (e.g., while one is traveling across state lines, etc.) have been fostered through Microsoft and other companies working with the OMG (Object Management Group) and the OGC (Open GIS Consortium).

4.5.2 Videologging

Videologging, employed by some larger transportation agencies, provides a comprehensive solution for collection of data that can be sensed from specially equipped vehicles. Camera-equipped vehicles routinely drive a jurisdiction’s roadway network to inventory conditions, sign locations, and other infrastructure features, all from a driver’s point of view. Variations on the theme include:

1. Integration of a Distance Measuring Instrument (DMI) for recording location by linear offset
2. GPS and/or inertial positions tagged to each video frame
3. The coupling of other instrument reading for roadway condition
4. Real time addition of attributes through semi-automated data entry or voice recognition
5. Precise location infrastructure through GPS-anchored laser-ranged offsets
6. Digital storage for video-linking for GIS-T and ITIS applications
7. The direct interface of video with straight-line diagrams.

The integration of Videologging with linear referencing may occur at various levels. At the simplest level, the videotape associated with any particular section of roadway is stored as a
roadway attribute in the common linear LRS. At a more advanced level, video clips or individual video frames are linked to specific roadway points or segments by the linear LRS, enabling users to graphically select a point on the roadway network and view the corresponding video clip or frame.

Data collected with the videologging effort, such as pavement conditions, is typically converted from the linear measures recording during data collection to the common linear LRS for integration with other roadway attributes. During the data collection process, operators may calibrate the recorded measures by comparing the on-board DMI to previously recorded ‘official’ measures at each reference point along a traversal. The data collection routes often involve travel in the opposite direction of established traversals (if bi-directional traversals are not available), and data collection along fragments of traversals, thus routines are commonly developed for converting between linear locations recorded during Videologging and the standard linear LRS.

Accurate and up-to-date sign inventories compiled from video logging generally pay for themselves from tort liability mitigation alone. The consolidation of multiple equipment types in the same dedicated video logging van is common practice, and substantial vendor literature is available on the Internet and from annual transportation conferences. Again, when fitting GPS to video logging equipment, the capabilities of WADGPS must be considered.

4.5.3 Data Warehousing

One definition of a data warehouse is a large, integrated, centralized database providing access by user-friendly means to query and analyze an organization’s information resources. Typically, a data warehouse integrates disparate operational databases into a unified system. In a transportation organization, a data warehouse might integrate various core transportation management systems, including roadway inventory, pavement management, safety, accident records, bridge structures, traffic management, vehicle registration records, etc.

Another operational view of what a data warehouse is that it is the data integration schema for pulling together all of the define wider set of corporate data assets. While a data warehouse may be considered certainly more than the data integration schema (for example, it includes routines for “data replication”, etc.), those constructing data warehouses spend typically the highest proportion of their time (sometimes as much as 70%) “inter-referencing” datasets, or providing indexes between data items. Often these indexes did not exist before and are a foundational to the operation of the data warehouse. “Indexing” is thus key to both LRS and data warehousing.

The data warehouse is typically read-only, with periodic data loads from the operational databases (as is being implemented by the Maine DOT), or it may be effectively developed in coordination with a transactional-based system where operational data are fully integrated and directly updated (as being developed with the Missouri DOT’s Transportation Management System).

Location is the key to integrating disparate transportation databases. Transportation-related data are typically located by one or more linear referencing methods, and in some cases by non-linear referencing methods (e.g., Cartesian coordinates for point features). The integration of disparate transportation databases must enable users to pose queries that combine data derived from different operational databases, related through location, but often with different LRM.

Examples of such queries include:
1. For a selected section of roadway (e.g., specified by the begin/end milepoints on a traversal), what roadways have an average traffic volume (AADT) of more than 5000 vehicles per day, with a pavement condition rating of 3.0 or less?

2. What are the accident rates for reconstruction projects completed from 1990 to 1994, for the three-year periods before and after completion of the projects?

Transportation spatial indexing is thus key to both data warehousing and LRS, and practically for both purposes DOTs building data warehouses for their LRS’s will likely rely on their operational LRS schemas.

Linear referencing poses a particular challenge to data warehousing. Linear LRS serves as the key to relating different databases, but does not readily lend itself to the relational model that is the standard for modern relational database management systems (RDBMS). SQL, the standard language for accessing relational databases, is based on set theory and the assumption that the order of rows in a table is arbitrary. However, the order of rows in a linear event table is important, being based on the sequence of milepoints along traversals (the same is true of time series data). By consequence, standard SQL does not include the functions needed for all desired operations on linearly referenced data.

As an example, consider roadway attributes along a single traversal from two event tables, as represented in Figure 38 below:

**Figure 38 Sample Roadway Attribute Segments**

Each segment is a length or roadway with common attribute values, for each of the respective tables. These attributes might be stored as in the sample event tables below (see Table 22Table 23 and Table 24).

**Table 22 Sample Pavement Event Data**

<table>
<thead>
<tr>
<th>Traversal ID</th>
<th>Begin milepoint</th>
<th>End milepoint</th>
<th>Pavement condition</th>
<th>Roughness</th>
</tr>
</thead>
<tbody>
<tr>
<td>123456</td>
<td>0.0</td>
<td>0.2</td>
<td>2.8</td>
<td>12.1</td>
</tr>
<tr>
<td>123456</td>
<td>0.2</td>
<td>0.3</td>
<td>2.8</td>
<td>11.0</td>
</tr>
<tr>
<td>123456</td>
<td>0.3</td>
<td>0.5</td>
<td>3.6</td>
<td>9.8</td>
</tr>
<tr>
<td>123456</td>
<td>0.5</td>
<td>0.8</td>
<td>3.2</td>
<td>10.5</td>
</tr>
<tr>
<td>123456</td>
<td>0.8</td>
<td>1.2</td>
<td>2.2</td>
<td>11.0</td>
</tr>
</tbody>
</table>
Table 23 Sample Traffic Volume Event Table

<table>
<thead>
<tr>
<th>Traversal ID</th>
<th>Begin milepoint</th>
<th>End milepoint</th>
<th>AADT 1996</th>
<th>AADT 1995</th>
<th>...</th>
</tr>
</thead>
<tbody>
<tr>
<td>123456</td>
<td>0.0</td>
<td>0.3</td>
<td>5600</td>
<td>4800</td>
<td></td>
</tr>
<tr>
<td>123456</td>
<td>0.3</td>
<td>0.6</td>
<td>3200</td>
<td>3000</td>
<td></td>
</tr>
<tr>
<td>123456</td>
<td>0.6</td>
<td>1.2</td>
<td>6000</td>
<td>5800</td>
<td></td>
</tr>
</tbody>
</table>

Now consider a query for the given traversal, from 0.0 to 1.2 miles, for a 1996 AADT of 5,000 or greater and a pavement condition of 3.0 or less. This requires the intersection of the two event tables, to determine where milepoints begin and end. The result set for this query would be:

Table 24 Result Set for Intersection of Sample Event Tables

<table>
<thead>
<tr>
<th>Traversal ID</th>
<th>Begin milepoint</th>
<th>End milepoint</th>
<th>AADT 1996</th>
<th>Pavement Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>123456</td>
<td>0.0</td>
<td>0.2</td>
<td>5600</td>
<td>2.8</td>
</tr>
<tr>
<td>123456</td>
<td>0.2</td>
<td>0.3</td>
<td>5600</td>
<td>2.8</td>
</tr>
<tr>
<td>123456</td>
<td>0.8</td>
<td>1.2</td>
<td>6000</td>
<td>2.2</td>
</tr>
</tbody>
</table>

Note that the first two records of the result set have the same attribute values, thus these two records could be dissolved with regard to their milepoints, as in Table 25.

Table 25 Result Set with Dissolved Records

<table>
<thead>
<tr>
<th>Traversal ID</th>
<th>Begin milepoint</th>
<th>End milepoint</th>
<th>AADT 1996</th>
<th>Pavement Condition</th>
</tr>
</thead>
<tbody>
<tr>
<td>123456</td>
<td>0.0</td>
<td>0.3</td>
<td>5600</td>
<td>2.8</td>
</tr>
<tr>
<td>123456</td>
<td>0.8</td>
<td>1.2</td>
<td>6000</td>
<td>2.2</td>
</tr>
</tbody>
</table>

In many respects, this is precisely the sort of functionality provided by dynamic segmentation in a GIS. However, there is an important distinction. In the GIS, the overlay is performed visually by simultaneous display of multiple event data sets. The user must then interpret the map to ascertain which roadway segments meet the query conditions. If the user wants to see the intersected events in a new table, an event overlay operation must be separately performed, against which the query can then be posed. In contrast, the operation in a relational DBMS would perform the overlay as part of the query and produce the desired result set directly (visual display is optional).

In standard SQL, there are no operators corresponding to the intersect and dissolve functions illustrated above. In fact, the intersection of the two event tables T1 (pavement) and T2 (traffic) can be performed as in the following pseudo-SQL statement (mp = milepoint):

```
SELECT traversal_id, greatest(T1.begin_mp, T2.begin_mp), least(T1.end_mp, T2.end_mp),
       T1.pavement_condition, T2.aadt_1996
FROM T1, T2
WHERE T1.traversal_id = T2.traversal_id AND
      T1.begin_mp < T2.end_mp AND T1.end_mp > T2.begin_mp
```
Although this is fairly straightforward for two event tables, extending this SQL construct to three or more event tables is an arduous task. For performing ad hoc queries, even the intersection of two event tables is too complicated for typical users. Furthermore, no such method exists in standard SQL for dissolving event records (a report can be generated that groups records by common attribute values, but would not account for any gaps in the sequence of milepoints). The problem, in essence, is that standard SQL has no method for processing records based on their order, as by comparing the end milepoint of one record with the begin milepoint of the subsequent record.

As a solution to these complications, custom applications are typically developed to perform the desired operations on event tables and to return result sets in the desired format. In addition, some vendors have provided extensions to standard SQL to perform the intersection (or union) of event tables. However, these types of extensions are usually performed separately and cannot be combined with a SQL query statement. Further spatial extensions to SQL address these issues.

4.6 Chapter Summary and Conclusions

Linear referencing is an essential component supporting modern business practices of public transportation agencies. Railroads and other transportation organizations also use LRS. Highway departments have kept large volumes of highway related data traditionally in records associated with static, fixed lengths of highway.

4.6.1 Progress Achieved

The previous chapter looked at the nature of “location” data and the various viewpoints and languages that have been used to describe and analyze it. This chapter has gone on to look in more detail at what is meant in the field by location referencing and, in particular, linear referencing methods. Both linear (x) and location (x, y) referencing identify a location with a code that can be interpreted without ambiguity by other systems. A nomenclature has been laid out.

4.6.2 Ten Key Observations

1. **Ontology:** It is possible to define a reasonably consistent nomenclature and set of concepts for LRS. About a dozen key terms define a significant part of the LRS field (for example: linear referencing system, linear referencing method, reference posts, mileposts, traversal reference point, offset, anchor section, anchor point, engineering stationing, control sections, event tables, and straight line diagram).

2. **LRS Implementation:** LRS has been implemented through two principal methods. These are, 1) sign oriented methods (such as mileposts and reference posts), and, 2) document oriented methods (such as SLD).
3. **Control Sections**: These establish a middle ground between route-milepoint and link-node schemes. Control sections break routes into manageable data management lengths. These may correspond to some artifact of the original construction.

4. **Event Tables**: These contain the attribute data for linear objects being modeled. Typically, they have been stored in a relational database table.

5. **Flatland Distance**: Consideration of the 3-D effects of roadways can affect length measurements. These effects are not as big as sometimes otherwise postulated as, a) many of the state-maintained roads (and hence with LRS) in many states are relatively flat and the distance correction is quite small (<5%), of the order of other sources of measurement error, and b) current DMI instruments incorporate 3D effects into their length measurements.

6. **GIS**: The growth of GIS has greatly facilitated the ease with which LRS may be performed with the use of COTS technology.

7. **Dynamic Segmentation**: This is the single most significant addition to GIS for transportation. The technology is however essentially currently in “Phase 1”. The use of DS allows significant benefits in normalizing (reducing) the volume of event data held and in facilitating various types of “network overlay” operation). In fact, because GIS’s cannot do network overlay directly (only polygon overlay), DS is a necessity for network based data storage and analysis.

8. **GPS**: Is becoming increasingly available and cheap to use. While the physical use of the technology is well understood, the institutional use of GPS as an art and a science has yet to be well proscribed. (This is the “data reconciliation problem”, otherwise called “the bridge over the river problem” — that is, the need to maintain a synchronicity between the accuracy of different datasets being maintained and integrated).

9. **GPS v LRS**: Rather than just being seen as an alternative to LRS, GPS in the field in fact has practically promoted the use of GPS, through the use of automated data collection vans which collect various types of highway data along linear traversals. The LRS definition of data may contain just the right amount of information for many classes of highway analysis (e.g., pavement, safety, congestion, etc.).

10. **Further Work**: This would consider as a minimum:

    1) Producing an even tighter lexicon of LRS with clear examples
    2) Providing agency-level institutional guidance on the set-up use of GPS (in particular as it related to LRS)

4.6.3 **Main Conclusions**

The efficient and appropriate storage of transportation data has always been a fundamental issue for DOTs. The fact that computer storage has become a lot cheaper has not totally done away with this issue. Even in the plain physical cost of storing data has been reduced, it still has to be
reviewed, cleaned, backed up and maintained and accessed easily. Thus, higher volumes of data do typically have a higher cost associated with them to the end user. New data collection technologies briefly described in this chapter (such as GPS) indicate that the volumes of data held by some DOT’s may increase by approximately a factor of four over a 5 year period at present times. As important as accessing this data in integrating this data and thus it is vital that mechanisms exist to achieve such operations.

The next chapter reviews some of the attempts that have been made to create generic data models to further the goal of the efficient and appropriate storage of transportation network data.
4.7 Chapter References


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Oak Ridge National Laboratories. Spatial Dataset Transfer Standards and ITS. ORNL Spatial Data Interoperability Project Site (http://itsdeployment.prj.utk.edu/spatial/).


Rowell, R. Theory and Practice in Linear Referencing at the Idaho Transportation Department, Proceedings, AASHTO Symposium on GIS in Transportation, Kansas City MO, March 31-April 4, 1996.

Scarponcini, P. Location Data Modeling Effort Final Report, prepared for Minnesota Department of Transportation, Graphic Data Systems Corporation.


5 Research Related to LRS

"The Choice is always the same. You can make your model more complex and more faithful to reality, or you can make it simpler and easier to handle. Only the most naive scientist believes the perfect model is the one that perfectly represents reality. Such a model would have the same drawbacks as a map as large and detailed as the city represents, a map depicting every park, every street, every building, every tree, every pothole, every inhabitant, and every map. Were such a map possible, its specificity would defeat its purpose: to generalize and abstract. Mapmakers highlight such features as their clients choose. Whatever their purpose, maps and models must simplify as much as they mimic the world."


5.1 Chapter Introduction and Purpose:

Three main summary LRS points may be drawn from the review in the prior Chapters 1 to 4:

1. Importance of LRS: Transportation agencies have issues with their current use and setup of LRS. Agencies that share an interest in the common transportation network often use different linear referencing systems and are thus not able to share data. At the heart of this research, it is recognized that the exchange and integration of diverse roadway-related information requires use of a common means of specifying locations. The strong importance of linear referencing to the policies and activities of transportation agencies was noted in Chapter 2.

2. LRS Field Difficulties: It was noted (chapter 4) that there are a number of possible issues commonly experienced with linear referencing. These include:

   1. Integration of data based on different linear and location referencing methods
   2. Relative efficiency of different database storage schemes and access methods
   3. Effect of updates to the roadway network (due to realignment, re-measurement, new construction, etc.) on linearly referenced data sets
   4. Limitations of one-dimensional measurements as applied to real-world structures
   5. Other related areas.

3. New Technology: The advent of new data collection and management technologies such as GIS, as a tool for integration, analysis and display of information.

This chapter provides an overview of research that has occurred mainly in the last 5 years to address these areas of concern. This research has largely focused on the construction of LRS

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data models. Prior work did not first set in place some of the field foundations that have been attempted in this work.

5.1.1 Requirements for LRM:

A few authors have made efforts to discern user needs for LRM. For example, the ERTICO Committee working in a European and ITS context settled on the following LRS wish list (Ertico, 1998):

1. It is truly international, i.e., it is not a country specific solution
2. It is able to address every street in the country
3. It is developed primarily for use with digital map databases, and is compatible with GDF (see Section 5.6)
4. It can be extended in the future to address other items, like points of interest (POI’s).
5. It supports a new generation of products combing ITS applications, e.g., navigation, emergency notification and traffic information.
6. It does not require pre-coding of locations and maintenance of very large tables
7. It does not require a master map database.
8. It does not involve a lot of work for map database producers, like mapping and inclusion of codes, and maintenance.
9. It helps to accelerate the industry, and facilitates the development and deployment of applications.

It is not clear however that the bulk of the work to generate LRS models has benefited from the specification of a clear set of user needs, such as summarized above.

5.1.2 The Search for a Generic LRS Model

Much of the LRS research to date has largely involved the search for a generic data model for linear referencing that would meet the information needs of diverse organizations while enabling them to more readily exchange information. This has been seen as a search, if not somewhat of a race for, the “Generic Linear Referencing Data Model”.

It has been a tenet of this thesis throughout that a more exclusive focus on defining a LRS model has occurred at some expense of a deeper analysis of the issues and context that the models were addressed to. The researchers and developers of these models were practically under time and resource constraints. They inevitably felt pressure to “produce something”, while realizing the “messiness” of the real world that Schon referred to (as reviewed in Chapter 2), and perhaps did not want for the sake of clarity of exposition to be over encumbered with it. Mapmakers and modelers attempt to reduce the real world to a ‘representable’ form. In Gleick’s words quoted at the beginning of this chapter, “mapmakers highlight such features as their clients chose”. Many of the data model researchers had limited prior direct background in LRS (though they often had a strong background in one of the supporting disciplines outlined in Chapter 3). However, in the words of thesis, “basic research” has been needed to at least better place in context and to validate these models.

A brief overview of current linear referencing data models is provided in this Chapter. These models include:

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1. NCHRP Project 20-27(2) Generic Linear Referencing Data Model
2. GIS-T Pooled Fund Study Linear Reference Engine
3. The Dueker-Butler model
4. Bureau of Transportation Statistics (BTS) Roadway Data Model
5. Geographic Data File (GDF)
6. Intelligent Transportation Systems (ITS) Locational Referencing System

The term “data model” is used in the widest sense, as the GDF as its name implies is really a file format (and some commentators might say this of the BTS data model).

It is not the intent of this thesis to provide the fully detailed information if the data models that can be obtained from the original sources. Practitioners of linear referencing who are involved in refining existing systems or developing new systems should be fully apprised of current research into linear referencing models. Chapter 8 does provide some further consideration and comparison of the models.

The main focus is made here on the NHCPR model. This is because it has been the subject of most attention, paid research and development to date, as well as wider input and appraisal.

A first general workshop on LRS were held by Lewis and Petzold at the AASHTO GIS-T Symposium in Albuquerque, New Mexico, 1993 and in Norfolk, Virginia, 1994. These helped focus some of the renewed field attention on LRS in the 1990's.

5.2 NCHRP Project 20-27(2) Linear Referencing Data Model

This section provides a brief review of the goals, technical approach and current institutional standing of the 20-27(2) road data model efforts. It is covered here in the most depth has it has to date probably gathered the most community interest.

5.2.1 Goal

Following research requests by various US state DOT’s on the LRS issues, the US National Highway Cooperative Research Program (NHCRP) formulated a project (NHCRP 20-27/2) to make recommendations on a national “best practice” LRS model and practices.

The NHCRP team took as its goals:

1. Meet common needs of as many DOT stakeholders as possible
2. Form a generic core that can be extended to specific applications
3. Facilitate sharing of linearly-referenced data across
   a. Modes and agencies
   b. Units and business areas internal to organizations
   c. Applications within those Units and Business Areas
4. Do the above in such a way that the data have a known and controllable level of Accuracy

A landmark publication, which helped stimulate research in the area of linear referencing, was the NCHRP Report 359, “Adaptation of Geographic Information Systems for Transportation” (Vonderohe et al., 1993). This report provides an overview of the adaptation of GIS for the
management and integration of the myriad types of information used for managing and administering transportation systems and facilities (otherwise known as GIS for Transportation, or GIS-T). It included the findings of NCHRP Project 20-27-1, Systems and Applications Architecture for GIS-T. It recommended that transportation agencies develop conceptual organizing principles founded upon the notion of location as a data integrator.

5.2.2 Technical Approach

A generic linear referencing data model was developed under National Cooperative Highway Research Program (NCHRP) Project 20-27(2). This model was based primarily on the results of a landmark workshop held in Milwaukee, Wisconsin in August, 1994. The workshop (subsequently called "the Milwaukee workshop") was attended by forty people, including a mix of 1) state DOT practitioners relatively knowledgeable in LRS, 2) software vendors, 3) consultant practitioners, and 4) academics. Professor Tim Nyerges of Washington State University acted as facilitator of the workshop.

The objective of the workshop was (or became) to develop a draft consensus conceptual data model for LRS. A data model was developed in the format of an entity-relationship diagram, which describes the key elements of a linear LRS and the relationships between them. Minor refinements were made based on inputs from various sources (Vonderohe et al., 1995 and 1997).

The data model uses a single linear datum, based on anchor points and anchor sections, to associate transportation data with multiple cartographic representations and multiple network models. The datum also enables transformations between different linear referencing methods, multiple networks, and cartographic representations at various scales. The data model, at the entity-relationship level, represents requirements for a generic data model for linear referencing systems, but is not intended as a detailed specification. Much of the subsequent discussion of the model has focused on how the model should be tested or implemented.

The proposed model acknowledges that a roadway system may be represented by different cartographic representations (e.g., by different GIS layers at different scales). Likewise, many different networks may be used to model the roadway system, each with its own set of links. The model makes use of anchor points and anchor sections to establish a single datum to which all cartographic representations and network models can be referenced. Business data are not directly referenced (e.g., by milepoints) to anchor sections; instead, they are referenced to traversals, which are built upon links. Anchor points and anchor sections are further described in the glossary, and in Vonderohe et al. (1997). Some specific cases and examples of the use of anchor sections are also described in Vonderohe and Hepworth (1996).

The NCHRP model (sometimes referred to as the 'Vonderohe model') was most recently described in NCHRP Research Results Digest Number 218 (September 1997), and hereafter referred to as the 'NCHRP Digest'. In the following sections below is a slightly more detailed consideration of certain key aspects of NCHRP 20-27-2. In summary, the purpose of the NCHRP generic data model is intended to be a generic data model that has these characteristics:

1. **LRS Requirements**: Meets the general requirements for LRS
2. **Extensibility**: Can be more readily extended, as needed, to meet the specific needs of various applications.

It is stated not to be or to provide:
1. A specification for LRS
2. A means for supporting the needs of all possible application areas.
3. Any guidance as to how the data model should be implemented

The model proposes the fundamental data objects of a generic LRS and the relationships between those objects. Some basic implementation issues are identified and posed as questions (e.g., “What is the best method for referencing ramps?”), but these issues are not specifically addressed by the generic model. This was not felt to be the purpose of the model, but rather defining a generic framework for local adaptation and use.

To some extent the model may then said to be have been created “‘top-down”, and needing local enhancement and instantiation to meet local application needs.

As already noted, at the heart of the NCHRP generic model are anchor points and anchor sections, which comprise a linear datum for referencing locations in the real world. These fundamental objects are discussed in sequence below.

The model is shown in Figure 39.

5.2.2.1 High Level Linear Operators

The 20-27 Project group established four spatial operator requirements for LRS, but potentially spatial analysis in general. The are shown in the following Table 26 Fundamental Spatial Operators:

<table>
<thead>
<tr>
<th>#</th>
<th>OPERATION</th>
<th>DESCRIPTION</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Locate</td>
<td>Establish position if an unknown point in the field by use of distance and direction references to other objects</td>
</tr>
<tr>
<td>2</td>
<td>Position</td>
<td>Translate a real world location into a database location</td>
</tr>
<tr>
<td>3</td>
<td>Place</td>
<td>Database location to a real world location</td>
</tr>
<tr>
<td>4</td>
<td>Transform</td>
<td>Convert from one linear LRS to another mapped on the same network</td>
</tr>
</tbody>
</table>

5.2.2.2 Anchor Points

An anchor point is “a zero-dimensional location that can be uniquely identified in the real world in such a way that its position can be determined and recovered in the field” (Vonderohe, 1987). The only attribute of an anchor point is its location description. Anchor points are the only features of the model that require external identification (in practice external identifiers are also typically used for traversals and traversal reference points). Anchor points serve the same purpose in the LRS as geodetic control points do in a geodetic datum. That is, they are the fundamental objects to which all other objects are tied.
Figure 2. The NCHRP Linear Referencing System Object Model (from Vonderohe, et al, 1995)
Many transportation agencies already maintain network nodes roughly that correspond to anchor points in that they represent specific spatial locations with external identifiers that enable them to be unambiguously located in the field. These nodes typically also serve one of the same basic purposes as anchor points, as the fundamental objects to which all other objects are tied (e.g., by offsets from the nodes). Typically, in many transportation agencies these nodes are also topological in that they are sequentially numbered along routes. Anchor points are non-topological and serve only to identify where things are located. The technical ramifications of this are discussed later.
The location description of an anchor point must make it possible to unambiguously locate the anchor point in the field. Thus, as stated in the NCHRP Digest, a bridge cannot be an anchor point, but “the center point of a specified end of the deck of a specified bridge” could be. In fact, the NCHRP Digest is ambiguous as to how specific the location description must be, because no recommendations are made for how accurately the anchor points must be located. While some would recommend against using street names to locate anchor points, this practice would be acceptable if the anchor point descriptions were updated any time a street name changed. The sole criterion stated in the NCHRP Digest is that it be possible to unambiguously locate the anchor point in the field, by whatever means.

A robust LRS should have a clearly documented standard for of the accuracy with which its anchor points (or equivalent) can be located in the field. The accuracy with which many transportation agency node locations are described (and can be relocated in the field) is often not clear from documentation that the agency may maintain. Typically, many network nodes are located at intersections, which generally have unambiguous locations. However, some intersections, such as the one illustrated below in Figure 41 may have ambiguous node locations depending on the distances between the various intersecting centerlines and a minimum distance tolerance between nodes. Depending on the distances between centerlines, some LRSs would use a single node, while others might distinguish three separate nodes (thus enabling more accurate location referencing).

Figure 41  Intersection with Ambiguous Node Location I

As well, some nodes may be located at bridges or other features (e.g., along stretches of roadway more than 20 km between intersections) for which the precise node location may be ambiguous in the field. For local roads, many nodes are at the end of the road, which in some cases is difficult to precisely locate in the field.

5.2.2.3 Anchor Sections

An anchor section is formally defined as a “continuous, directed, non-branching linear feature, connecting two anchor points, whose real-world length ... can be determined in the field.” (Vonderohe, 1997). The direction of an anchor section is determined by specifying ‘from’ and ‘to’ anchor points as attributes of the anchor section. Anchor sections are non-overlapping, thus they provide a fundamental referencing space for the linear features being modeled. Anchor sections also need identifiers. These enable one to determine the correct path between ‘from’ and ‘to’ anchor points, which may be ambiguous as in Figure 42 below (note: an anchor section can not be described as “from node A to node B” since there are two paths between A and B). In fact, the path between
anchor points is nearly always ambiguous in the NCHRP model since anchor sections may pass through other anchor points.

**Figure 42** Intersection with Ambiguous Node Location II

The above figure could indicate for example multiple anchor sections between two anchor points.

Many existing DOT transportation model network links correspond roughly to anchor sections in some respects. However, they differ in some fundamental ways that should be well understood. Typical transportation links generally correspond either to entire numbered or named roads, or to lengthy sections of roads (e.g., between interchanges on the 100 series roads). The nodes provide points of known offset along a link, which can effectively serve as calibration points (or ‘control points’) along GIS centerlines for the offsets along the lengthy links. In contrast, anchor sections do not have any intermediate points with known offsets, so that the offsets of intersections and other features along their lengths can only be determined along GIS centerlines by linear interpolation along their entire lengths. (Note that linear interpolation can take place along centerlines with coordinates stored in 3 dimensions, thus assuring interpolations along true linear distance rather than horizontal distance. If centerlines are stored with 2-dimensional coordinates, then the only way to improve the interpolation is to decrease the distance between control points.)

As explained in the next section, (Chapter/section 5.2.2.4) anchor sections comprise a linear datum to which all traversals and linear referencing methods and cartographic representations are tied. In many DOTs the LRS provides a standard set of traversals and linear offsets, but does not strictly function as a separate linear datum to which traversals can be referenced. That is, in existing LRS models the links are the traversals, and are not being referenced to a separate set of anchor sections. This is not viewed as a deficiency in existing LRS; it is simply a subtle difference between the NCHRP model and many standard LRS models.

Anchor sections must have identifiers that enable one to determine the correct path between ‘from’ and ‘to’ anchor points. No guidance is provided in the NCHRP model for how these identifiers should be assigned. However, the principle NHCRP author, Vonderohe, states in the ‘Discussion and Closure’ section, that he believes they should be neutral identifiers which can then be associated with one or more official road names, or with cartographic representations that enable them to be located in the field. In practice, a stable identifier is preferred that does not depend on jurisdiction or road class (which may change over time, particularly for ‘local’ roads near urban areas). Road names or numbers tend to be more stable than jurisdiction or road class, thus road names are often used to identify traversals (anchor sections, as precisely defined in the NCHRP Digest,
have not yet been field implemented, but the issue is basically the same for traversals). Others would argue that random numbers are the best unique identifiers, and that the conversion to these random identifiers from more user-friendly referencing can be made through automated data entry systems. There is no definitive ‘best practice’ for how to identify anchor sections (or traversals). The best solution for a particular agency often depends on their existing field practices and road naming conventions. For traversal identifiers, both roadway names and random numbers have been used as the basis of successful linear referencing systems. Given that the issue is not addressed in the NCHRP model, it is beyond the scope of this current report.

Typical transportation agency model links are identified by their starting nodes, and directed by the sequence of nodes along a numbered or named roadway. Because they are often numbered sequentially, the link identifiers are not strictly neutral. In fact, the sequential numbering of node identifiers may result in multiple nodes at a single intersection, a problem discussed in Section 4.3.

Anchor sections can cross without sharing an anchor point (e.g., at an overpass). Anchor sections can also pass through at-grade intersections without encountering an anchor point. At odd-valence intersections (that is, where an odd number of links come together), at least one anchor point is needed, but it can be for a single anchor section. For example, Figure 43 below shows a ‘cut’ or ‘ramp’ providing a one-way turn between two roadways. (Note, there is no definitive term for this one-way connector; ‘ramp’ is often reserved for grade changes). The ‘cut’ can be represented by a separate anchor section, but the endpoints of the ‘cut’ do not have to be anchor points for the roadways themselves. This does not have any particular implications for changes in typical existing DOT models, but is included here to provide a better understanding of anchor sections as described in the NCHRP model. This also emphasizes the fact that the NCHRP model does not specify where anchor points should be located, nor where anchor sections should be defined.

As proposed in the NCHRP Digest, a divided highway with separate roadways for each direction of travel requires an anchor section for each roadway. This is consistent with the typical separate links created for divided highways, created in most existing DOT LRMs, which appears to be good practice at least from a data management perspective. With regard to the implementation of divided highways in GIS, on a small-scale map the divided highway might be represented by a single line, in which case the separate anchor sections would be associated with the single line for display at small scale. At larger scales, the separate anchor sections would be associated with separate centerlines.

Figure 43 Example of a 'cut' Between Two Roads at an At-grade Intersection
5.2.2.4 The Linear Datum

In the NCHRP model, a linear datum is comprised of the complete set of anchor sections and anchor points. The linear datum is not a network, in that it does not tell us how to get from “here to there”. Instead, the linear datum only tells us where things are.

A typical DOT LRS differs significantly from the NCHRP model at the level of the linear datum. At this level, the nodes differ significantly in function from the anchor points. Anchor points and anchor sections serve to define the linear datum upon which one or more linear networks (each with its own traversals and linear referencing methods) can be defined. In the typical DOT LRS, the nodes and links serve to define a standard set of traversals with a single LRM, which typically is not used for converting between LRMs. Also, more importantly, the LRS nodes are typically sequential along pre-defined roadways. In contrast, anchor points have only location descriptions, with no sequential numbering along named or numbered roadways, and serve only as the endpoints of anchor sections (which have no particular sequence).

In the NCHRP model, the anchor sections of the linear datum must be non-overlapping. Likewise, in the typical DOT LRM, links are non-overlapping. This is a very important similarity between function of the links as typically used in a DOT and the NCHRP anchor sections. This may facilitate the typical DOT LRS to function effectively like a linear datum, even though its underlying structure differs from the NCHRP model.

For field implementation of network linear referencing, it has been proposed to put a national set of linear reference points (or, anchor points) in an universal datum in place (Fletcher, et al, 1996). The following specifications were identified as a set of partial requirements for a unified linear datum. These specifications represent the datum users’ expectations.

1. The purpose of the datum is to transform locations between the real world space and data world space(s) and to project positions between data spaces.
2. The datum needs to be a consistent, nationwide framework accessible to public and private customers.
3. The datum will be used in multiple public domain and proprietary data bases.
4. Although the datum itself must be in the public domain, many applications using this framework will be proprietary.
5. The datum needs to be able to control location at multiple levels of resolution (e.g., highway location, roadway location, lane location).
6. The datum needs to be able to control locations determined by many different methods.
7. Each functional domain has distinctly different accuracy specifications. This is a function of either the smallest objects (i.e., the highest resolution) in the domain(s), the need to discriminate the relative distance between two objects or the precision of the location measurement devices.
8. Navigation and traveler information functions need 3-5 meter positional accuracy. This may be derived from the need to discriminate individual vehicles.
9. Field location datum objects and reference objects need to be identified easily in the field. These objects also need to be fixed, stable and recoverable over long periods of time (decades, if not longer).
10. The unified datum should be domain content (i.e., application) neutral.

5.2.2.5 Distinction Between the Anchor Sections and Traversals

In the NCHRP model, anchor sections are very distinct from traversals, a distinction that should be understood for contrasting the NCHRP model with the typical DOT existing LRS. Anchor sections are non-overlapping, and constitute the linear datum to which all other objects are tied. Traversals are built upon links and nodes that, in turn, are related to anchor sections and anchor points. Traversals can overlap, and different LRMs can be employed on a given set of traversals.

In one conceptual sense, anchor sections may be viewed as another layer of abstraction between traversals and geometry, so that either one can be improved and then remapped onto one another.

In a field practice sense, anchor sections can be viewed as a special type of traversal, which in theory can be used as a linear datum by all LRMs and all cartographic representations. A location on the linear datum is specified as an offset along an anchor section from the 'from' anchor point. As a means of locating a point, the anchor section is equivalent to a traversal.

As noted earlier, current COTS GIS packages do not currently directly ‘support’ the NCHRP model. There are in COTS no built-in feature types that correspond to anchor points and anchor sections, or which serve their function as a linear datum to which all networks and cartographic representations can be associated. To implement the NCHRP model, anchor sections would be implemented as another set of traversals. For example, this would be as a separate route system in COTS GIS such as Arc/Info. Other linear referencing methods would then be implemented with their respective traversals (or ‘route systems’). Special routines would then have to be developed to convert between the ‘linear datum’ of ‘anchor sections’ and other supported linear referencing methods. While this is in theory doable, it practice it would be cumbersome.

In the typical DOT LRS, the links correspond roughly to anchor sections, and also to traversals. No distinction is made between the ‘linear datum’ function of the links and their use as traversals for locating things along the roadway network. Again, one may emphasize that this is not a deficiency in the typical DOT LRS. In fact, it may make good sense in terms of the practical implementation and application of the LRS.

5.2.2.6 Support of Multiple Linear Referencing Methods (LRMs)

The NCHRP model is designed largely to support the use of multiple LRMs and translations between those LRMs. As noted in Chapter 4 section 2, support for multiple LRMs to meet various user needs is a key goal of a robust LRS. This allows different user communities to continue with their existing business practices that may have a more or less rationale justification for them or just be based on historical precedent.

This was indeed one of the defining criteria in the development of the NCHRP model, which relies on the linear datum (that is, anchor points and anchor sections) as the fundamental referencing space for converting between multiple LRMs (which may even occur on multiple network representations).
5.2.2.7 Use of Traversal Reference Points

The NHCRP model supports the use of “traversal reference points”. Existing DOT datasets typically have nodes, which may be used as traversal reference points, to which other features are referenced. That is, feature locations could be referenced as an offset from an existing node along a network link, rather than as an offset from the beginning of the link.

5.2.2.8 Support of Multiple Cartographic Representations

The NCHRP model was developed to support the use of multiple cartographic representations (for example, changes in scale, projection, etc.) of the linear transportation network. That is, the same linear datum (anchor points and anchor sections) can be related to multiple cartographic base maps.

Many DOTs LRS while in theory free to be used at different cartographic projections have often in practice be tied to one level of network representation (for example, the 1:24,000 state highway base map). However, DOT’s do produce maps at different scales and projections at certain times. Many states use their own state plane coordinate systems for many of their cartographic products. In larger states such as Texas and California, the state is divided into more than one state plane coordinate system. Other states have converted some cartography from NAD 27 to NAD 87, but not yet all map products.

5.2.2.9 Directionality of Linear Objects

Directionality is established in the NCHRP model for anchor sections, links and traversals. This is done in order to support the required translations between the linear datum and the traversals and linear referencing methods tied to the linear datum.

Many DOTs across the country have established both simple and more elaborate methods to establish directionality for node numbering. For example, one scheme may be for north directions start in the “100’s” (or “1000’s”, south 200’s (or “2000’s”), etc. This is a practically important aspect that is not requirement of the NCHRP model. Also, there is no requirement that nodes be sequentially numbered along named roadways. This may more readily result in the establishment of multiple nodes at some locations. In general, this is an undesirable situation in that multiple references may be used for the same location. The possible impacts of this deviation from the NCHRP model are further discussed in the evaluation of the node placement issue (see Chapter/section 4.3).

5.2.2.10 Proposed Methodology for Design of a Linear LRS

Vonderohe and Hepworth (1996) proposed a methodology for design of a linear LRS that will meet specific accuracy requirements. The methodology was developed from geodetic engineering principles and techniques used for designing geodetic control networks. A complete mathematical development is provided founded upon the law of propagation of random error and the statistical analyses of systems of redundant measurements.
5.2.3 Overall Technical Standing of the NHCRP Model

Further review will be made in later Chapters (in particular, Chapter 8) on the NHCRP model. Five basic key summary points maybe made at this stage:

1. **Application Data Model:** The model is simply that -- it is a data model. It is does not provide any detailed advice on dealing with LRS field issues or how in particular in any depth how to apply the model itself in the field.

2. **Model Contribution:** The model is itself is a significant contribution, relatively elegant in form. The major contribution of the model may not necessarily be the exact model form itself, but rather that:
   a. It represents *one* reasonable model form
   b. The introduction of the concepts of anchor points and sections

3. **Model Level of Detail:** The model is basically fairly high-level in form and treatment and provides “one model of doing business”. With regard to the model as laid out in Figure 39, it may be seen that the richness of relationships permitted is fairly limited and may not fit the user needs of the wider transportation information communities. For example, having regard to the right and center of the diagram, the model describes that “Traversals” are made up of one or many “Links”. For many applications, it may be desired to construct traversals from many other network components, such as for example, “segments”, “control sections”, or other possible network components, etc.

4. **Anchor Points and Anchor Sections:** The model provided in Figure 39 indicates that the network may be created without a ‘datum”, which therefore does not enforce the use of anchor points and sections. This facilitates the potential use of the model with planning networks (such as used for transportation network analysis models) that do not necessarily directly tie to a cartographic datum.

5. **Basis For Expansion and Improvement:** The model was perhaps never seen as an endpoint in itself but a basis for expansion and improvement. This is occurring through a current subsequent NHCRP funded project and its consideration for use by state DOTs.

5.2.4 Institutional Standing

The NHCRP project team felt it had provided a framework for sharing and integration of linearly-referenced data at a known and controllable level of accuracy. They felt that the field design driven by accuracy requirements for transportation business data. The model was derivable from business functions and was based on a geodetic engineering design method. The NHCRP team felt they had created a “Least-cost configuration for referencing system guaranteed to meet accuracy requirements at a specified level of certainty”.

It appeared in the year or two after the “Vonderohe” was finally formally reported, few state DOT’s decided to formally implement. However, more recently a number of state DOT’s have put in place initiatives to implement the model (for example, see Minnesota and Iowa DOT, 2000).
5.3 GIS-T Pooled Fund Study Linear Reference Engine

This section provides a very brief review of the goals, technical approach and current institutional standing of GIS-T Pooled Fund Study Linear Reference Engine road data model efforts. It is not covered in great depth as it basically followed the 20-27(2) approach.

5.3.1 Goal

As part of the GIS-T/ISTEA Management Systems Pooled Fund Study (PFS) (Fletcher, 1995), specifications and a prototype were developed for a Linear Referencing Engine (LRE). The LRE was proposed as a robust data model framework in response to perceived needs among the GIS-T community for development of a standard model that could work with different linear referencing methods. The LRE was proposed to demonstrate location transformation between multiple referencing methods. It was developed using Borland's Delphi software.

5.3.2 Technical Approach

The LRE supported reference points, milepoints, anchor sections and traversal classes. Although the LRE successfully demonstrated the intended transformations, it did not address many of the "real world" concerns associated with linear referencing.

The model generally followed the lines of the NHCRP model described above and is not thus further reviewed here.

5.3.3 Institutional Standing

Phase B of the PFS included implementation of the first-draft data model developed under NCHRP 20-27(2), described above in section 5.2. One of the findings led to a refinement of the NCHRP generic linear referencing data model (Vonderohe et al., 1997).

5.4 The “Dueker-Butler” Model

This section provides a very brief review of the goals, technical approach and current institutional standing of Dueker-Butler road data model efforts.

5.4.1 Goal

A GIS-T enterprise data model has been developed over the last five years by Dueker and Butler (1997). The original genesis seems to have been the 2-27(20 LRS workshop.

This is a more general transportation-land-use model than the NCHRP 20-27(2) model; it is intended to support enterprise sharing of digital roadway databases (originally for the Florida Department of Transportation). Its genesis however lies with the 20-27 model and in some measure is an extension of it.

5.4.2 Technical Approach

The model incorporates:
1. Non-linear location referencing (e.g., by GPS)
2. Area events,
3. More detailed cartographic entities and
4. Non-transportation features.

developed in a series of steps: the basic model, adding topology, adding cartography, adding a linear datum and supporting non-transportation features. This detailed presentation is instrumental in describing the model and its intended purpose. The authors then discuss issues associated with implementing the model, including sample physical database designs. The Dueker-Butler model is described in data model format in Figure 44.

One of the key differences of the Dueker-Butler model is that it extends “location” to non-linear referencing systems. They therefore use the term “linear location referencing system” in place of the 2-27 “linear referencing system” to make this clear.

There are also a set of more detailed differences between the Dueker-Butler model and the 20-27 model, for example, how traversals are dealt with. The model is not examined in further detail here as much of the focus of the model is not strictly linear in its application focus.

More generally, one of the authors in a recent paper (Butler, 2000) notes:

_The solution to overcoming these differences is not to try to make everyone adopt a single GIS-T. There were legitimate differences in requirements that led to today’s application-specific definitions and representations of transportation features and their geometry.... The solution is to embrace diversity within an unifying enterprise data model for GIS-T._

5.4.3 Institutional Standing

The model is being used by one of its progenitors in Hamilton County, TN. It is not clear if other agencies have adopted the model yet. Work on the model seems to have led to some useful review, dialog and tune-up of the 20-27 model.

The work would seem a significant general contribution. It needs to be made clearer how it fits in with the other data models described here, including GDF.
Figure 44 Ducker-Butler Enterprise Data Model
5.5 **FGDC/ BTS “Roadway Data Model”**

This section provides a brief review of the goals, technical approach and current institutional standing of FGDC/BTS road data model efforts.

### 5.5.1 Goal

FGDC has as its goal to promote, "the coordinated development, use, sharing, and dissemination of geographic data". The FGDC created the ground Transportation Subcommittee in January 1992 to address data issues involving transportation features. The objectives of the Subcommittee are:

1. Promote standards of accuracy and currency in ground transportation data which is financed in whole or part by federal funds
2. Exchange information on technological improvements for collecting ground transportation data
3. Encourage the Federal and the non-federal community to identify and adopt standards and specifications for ground transportation data, and
4. To promote the sharing of ground transportation data

Transportation is one of the seven layers identified in the National Spatial Data Infrastructure (NSDI).

The stated purpose of the road model initiative was to, "Provide a logical data model for identifying unique road segments which are independent of cartographic or analytic network representation. These road segments will form the basis for maintenance of NSDI framework road data (though transactions of other means), and for establishing links among road segments and attribute data". (FGDC, 1998).

### 5.5.2 Technical Approach

A series of technical meetings were held around the country, mainly with local agency officials. It was noted that many of the proposed models, such as the 20-27(2) model, or, spatial data standards, such as SDTS, were quiet complex to set up and operate. It was felt that the needs of local agencies could be met by a more “fundamental” and basic schema.

A standard was thus proposed that numbered physical highway segments independent of cartographic representation, scale, level of detail, or network application. The standard includes:

1. **A Framework Transportation Segment Number (FTSEG)**
2. A mandatory set of attributes to be collected for each segment
3. The rule that each FTSEG begins and ends at a **Framework Transportation Reference Point (FTRP)**
4. An identification code and attributes for each FTRP
5. A process for assigning, modifying and recording transportation segment identification codes
6. A proposal for a national registry for transportation segment identification.
It was stated (FGDC, 1999) that the standard can be extended to cover in future to cover other transportation modes, such as railroads.

In pursuit of wider support of LRS issues, in addition BTS also released in 1998 a ‘LRS in GIS’ CD-ROM to, “assist state and local transportation agencies and professionals with the implementation of linear referencing systems in GIS”. The CD-ROM contains about 100 scanned documents relevant to linear referencing and GIS, including many DOT and other working papers. Also included are a glossary of terms (with definitions from multiple sources), and a resource guide written by BTS to provide an overview of topics on implementing LRS in GIS. Topics are linked to original source materials, and all documents are searchable by key word and author or title. The CD has no digestion or interpretation of the LRS material. This is part of the challenge this thesis has addressed itself to.

5.5.3 Institutional Standing

BTS was proposed as the maintenance authority for the standard. BTS has gone through some significant organizational changes in 2000, with significant staffing changes, including the progenitors of the framework. BTS is also currently reviewing its data development and research activities. At the present time, further support for the framework is in question. It is not certain, despite the significant effort that has gone into date, that further support or development of the framework will occur at least in the short-term. One of the concerns mentioned is that though the concept of the framework is relatively clear, the 100-page accompanying manual has not been readily interpretable by end-users.

5.6 Geographic Data File (GDF)

This section provides a brief review of the goals, technical approach and current institutional standing of GDF road data model efforts.

5.6.1 Goal

GDF is a European (CEN) standard that is used to “describe and transfer road networks and road related data”. It stated as being much more than a generic GIS standard, because GDF gives rules how to capture the data, how the features, attributes, and relations have been defined. The data structure of GDF supposedly makes it well set up for Intelligent transportation Systems (ITS) applications. However, its intended primary use is for car navigation systems, but it is very useable for many other transport and traffic applications”. (Intergraph, 1997).

GDF was fist developed as a standard in various projects from 1985 to 1992. Version 2.0 was published in 1992. It was subsequently followed by 2.1 in 1993 and 2.2 in 1993. The current version is 3.0.

GDF is seen as:

1. A reference frame for data production. (It provides a data dictionary, data description rules, and definition of quality concepts)

2. A data model (it provides mappings between
   a. Real world objects and real world objects
b. Planar graph and non-planar graph objects).

3. An exchange format. (It may be used to translate between different vendor applications).


Figure 45 shows the general GDF data model.

5.6.2 Technical Approach:

Technically, GDF specifies the format of an ASCII file for containing geographic data. It particularly focuses on the representation of a road network. However, it may also be used for other types of geographic data. Its primary use will be for car navigation systems (Bosch, Philips, Volvo, etc.), but it is very usable for many other transport and traffic applications...".

As with any model of geographic reality, simplifications of the real world must be made, and involve various tradeoffs. Simplifications must be made in order to generalize. GDF has these limitations in common with any geographic data model and thus there will always be uncertainties in interpreting any geographic data set or sets due to the abstract data of the data models.

Advantages of the GDF data model are the possibility to share geometrical and topological information by different features or separate information layers according to data models defined by GIS.

GDF divides the real world into individual objects. There are three main levels of representation within GDF, each having a separate data representation. Level 0 is the lowest level of representation and includes a geometrical representation formed by 2D and 3D coordinates. From this a topological structured planer graph is built, consisting of nodes, edges and faces ("graph primitives"). Level 1 is the semantic level of simple features, which can be points, lines or areas. Level 2 is complex features, such as networks. These may be non-planar.

GDF provides definitions of numerous feature classes, their representations, attribute types and relationship types and relationship types, compiled into four data catalogues. Features and related attributes are semantically grouped into feature themes, such as Roads and Ferries, Administrative Areas, Services, Waterways, Services and Bridges, etc. GDF Attributes address characteristics of exactly one feature, realized by a 1:1 relation. However, property information that involves several features is modeled through relationships. Attributes in GDF include functional road class, street name, household numbering, location referencing code, traffic flow, road width, travel time (per road element), speed restrictions and height of pass. GDF relations include forbidden turns, service along the road, grade separations describing bridge or tunnel levels, etc. Aggregation can occur – for example, grouping by road number.

The relative complexity of GDF (due to its flexibility to be a conceptual model for any geographic information) is also well noted. However, others argue that this is not a problem as GDF maps may be defined with a variety of complexities (Ertico, 1997).

GDF uses a feature-based model, similar to DIGEST/VPF and USGS DLG-F (Hickman, 1995). This allows use of a topologically structured planar graph at the primitive
geometry level, while supporting non-planar transportation network components (seamless, over-passing road segments) at the simple feature level. GDF also supports multi-scale feature representations, and explicit relationships between features.

GDF provides some basic support for linear location referencing. GDF contains a limited linear referencing data model. Attributes in GDF are associated with a "feature in such a way that they reference a certain part of it. These attributes are called 'Segmented Attributes.' With line features, the part, which is referenced by the segmented attributed, is defined by a 'position from' and a 'position to' value. These positions represent the curvimetric distance" [Ertico, 1995]. Curvimetric distance is based on the representational geometry, which may not be as robust as the linear location referencing used in the other transportation profile proposed by Dueker and Butler. Version 3.0 of GDF (CEN, 1995) accommodates addresses in section 5.2.10 (Address Area).

There is some difference of exact view in US circles on how to best characterize GDF. This may in part reflect that there has been limited public exposure to it in the US. On one hand, some of the commercial map vendor companies have adopted GDF as the basis for their enterprise model of geographic data storage. GDF is fairly fully featured allowing potential use for more than just transportation data storage. Microsoft, ETAK and Rand McNally are examples of companies who are using GDF.

On the other hand, others view GDF just as a file exchange standard, or a transportation data exchange standard, not an operational model, like the NHCRP or the Dueker-Butler enterprise GIS-T data models. GDF has certain similarities to SDTS, which can potentially be used to transfer most anything in topological vector form. GDF does imply that the working data model of the source and receiver includes a fully topological, vector-based design.

GDF is an integrated topological data exchange standard. The Dueker-Butler model for example supports unbundled approaches, that is, keeping all four parts (cartography, topology, attributes, and datum) separate. GDF is the opposite approach, which, like SDTS, puts them all together. In so doing, it precludes several types of data exchanges that are important. It also is really a lower-level approach that deals in primitives, like one block represented by a line with two edges. Features such as an entire transportation route are complex features in GDF. Methods of dealing with routes and LRS in GDF exist but are quite limited.

GDF is focused on the domain of large-scale topographic maps, ranging from 1:5000 to 1:25,000. The GDF web page contains a full technical description of GDF in the 500-page reference document.

5.6.3 Institutional Standing

Organizationally, GDF has been worked on in Europe for about a decade. The work originally started as an effort to coordinate a format for car navigation systems, though that main scope has been broadened over the years. However, car navigation systems remain the principal commercial driving force at the current moment of time. A couple of major Europe-wide initiatives have been carried out using GDF.

8 The Web site homepage for GDF support: http://www.intergraph.com/ehg/gdf
Figure 45 GDF General Data Model
In Europe, the GDF standard has become increasingly recognized in the last five years. The GDF standard is well established as the most advanced data model and data format for transportation. GDF has been used less in the US to date. The Canadian GIS-T standards recommend the use of the DIGEST standard (TAC, 1995).

GDF databases have been captured for more than 6 years now. These include by for example by:

1. TeleAtlas
3. ETAK (US and UK)
4. Rand McNally (The use of the GDF data model is core and foundational to the Rand McNally (RM) NavMaker Database Project).

The use by major industry players is felt to demonstrate GDF's general status and usability.

It is argued highly likely that GDF (in the future ISO version of the standard) will become the state-of-the-art technology for digital map databases for ITS in Europe as well as in the US. This is because it represents not only an internationally agreed specification but also huge data volumes captured according to GDF and being available for applications (European and US map coverage with detailed contents).

GDF has been implemented by the production of extensive European digital road map databases with a rich content for ITS applications such as car navigation, fleet management, etc. Version 1 was produced in 1990 and Version 2 in 1993. It went through a period of strong attention and revisions from 1993 to 1995, culminating in GDF 3 in 1995. It was last substantially updated in October 1995 and with very minor revisions in June 1996. It is not certain how much GDF is currently under wider active development.

Different users of transportation information demand different transportation models. It is not clear currently which will be favored between the CEN GDF and the EU backed Road Administration Data Exchange Format (RADEF) in Europe. GDF best suits the navigation community, while RADEF is more suited for public road administration. Different users of transportation information demand different models Administration Data Exchange Format (RADEF) in Europe. This implies the need for innovative solutions across a wide global range of diverse technologies and requires the development of standard transportation interfaces.

5.7 Intelligent Transportation Systems Locational Referencing System

This section provides a brief review of the goals, technical approach and current institutional standing of ITS road data model efforts.
5.7.1 Goal

The objectives of Intelligent Transportation Systems (ITS) are motivating the need for seamless integration of disparate transportation data sources. ITS incorporates a broad range of technologies, but one of the key concepts is that real-time information be provided directly to the traveler to aid in navigating from point to point. Relevant information provided to the traveler would include shortest path, traffic conditions, construction projects, alternate routes, etc. These applications fall under the umbrella of Advanced Traveler Information Systems (ATIS), Advanced Passenger Transportation Systems (APTS) and Advanced Traffic Management Systems (ATMS).

A great challenge for ITS is in providing location referencing information, across wide geographic areas and from different kinds of databases, by methods that can be properly interpreted and integrated by other ITS applications.

A major center for research in this area is the Oak Ridge National Laboratories. There were three specific recommendations on ITS data transfer standards:

1. **ITS Focus:** When developing an ITS spatial data interchange standard, the interchange format must take into account the special needs generated by ITS use, including international standardization, database update, metadata requirements, ITS features and attributes, and compatibility with the ITS location referencing standard. The emphasis for this will not be to create a new standard ‘from scratch’ but rather to make existing standards and standards under development truly useful for ITS.

2. **ISO Support:** Support development of International Standards Organization Geographic Data Format (GDF) for ITS. The ISO GDF standard will enable delivery of spatial data to all ITS customers in GDF format.

**Implementation Support and Outreach:** Since transfer standards by themselves transfer features, not directly usable databases, they must be tailored to meet ITS end-user needs with application-specific information on data dictionary items, recommended practices, and metadata and data quality, and usage documentation. This tailoring includes collection of this information, structuring it into useful documentation and software, and deploying it to ITS application communities.

Oak Ridge National Laboratory (Oak Ridge, 1997) was tasked by the Federal Highway Administration to:

1. Review the requirements of ITS applications for spatial data and location referencing
2. Develop consensus positions on spatial database issues, and
3. Determine whether any Federal action is necessary to ensure those needs are met.

The research has recommended development of a national ITS datum, a set of nodes and links which all ITS users would have available as a standard non-planar network for referencing purposes (Goodwin, 1996; Siegel et al., 1996). The ITS datum would serve as a national network of ground control points that would anchor spatial references between different databases. Translation between different location referencing methods would be accomplished through the common ITS datum.
5.7.2 Technical Approach

To work with the proposed ITS datum, the research has also proposed development of an interoperability protocol framework called the Location Reference Message Protocol, or LRMP (Goodwin, 1996; Goodwin et al., 1996; Goodwin et al., 1995). This protocol would provide a framework for standardizing location reference message formats to meet ITS needs. Multiple formats would be required to support the different kinds of location referencing that would be used by ITS applications. The LRMP is being developed under ongoing work on the ITS project.

The ITS datum initiative is an excellent example of the problem at hand for ITS. As vehicles receive local ITS information, neither the information provider nor the various receiving vehicles know what LRS the other is using. How can linearly referenced data be exchanged between otherwise disparate users? The ITS datum is visualized as a set of nodes and links which all ITS users would have available as a standard network for referencing purposes. This would create a national network of ground control points that would anchor spatial references between different databases. Translation between different location referencing methods would be accomplished through the common ITS datum. The search for a generic linear referencing data model is an extended application of this concept, and includes input from other models such as the NCHRP Project 20-27(2), the GIS-T Pooled Fund Study Linear Reference Engine, and the Dueker-Butler.

5.7.3 Institutional Standing

The current institutional status of the ITS datum is unclear in terms of its formal adoption. Technical work on the standard is apparently still proceeding on some level. However, its wider institutional adoption at the current time is unclear. It seems that highway authorities are unlikely to uniformly adopt it themselves without a mission and a mandate to do so. Further discussion of ITS Datum institutional standing is contained under GDF.

5.8 Spatial Data Transfer Standard (SDTS)

This section provides a brief review of the goals, technical approach and current institutional standing of SDTS.

5.8.1 Goal:

In the US, the National Spatial Data Infrastructure (NSDI) is supported by the FGDC (Federal Ground Data Committee). It is an initiative to forge exchange standards for geographic information. It was felt that without such standards there was a concern that past investments (including governmental) in digital geographic data could be lost. The progenitors of SDTS see it more than just a “transfer standard”, but rather as a package that contains:

1. Geo-referenced spatial data, plus
2. Information on how to best use the data.

The principal result of this effort is the Spatial Data Transfer Standards (SDTS).
5.8.2 Technical Approach

To divide the problem into manageable pieces, SDTS is proposed to be implemented as series of pre-defined profiles. To maximize storage, the international ANSI/ISO 8211 will be followed for file size reduction.

Profiles are defined as being subsets not supersets of SDTS. The most significant profiles in the context of this research include:

1. Topological Vector Profile (TVP) was for developed point, line, polygon, and composite vector data, including USGS Digital Line Graph (DLG) and the Bureau of the Census Topologically Integrated Geographic Encoding and Referencing (TIGER) data files.

2. Raster Profile (RP) is currently available in draft form only, but will transfer image data, digital terrain models, and other gridded data. When complete, the RP profile will facilitate USGS Digital Elevation Models (DEM) and Digital Orthoimage Quadrangle (DOQ).

3. Geodetic Profiles (High Precision Point Profile or SDTS Part 6). This profile was developed by the National Oceanic and Atmospheric Administration - National Geophysical Data Center (NOAA-NGDC) and the USGS to transfer control points.

4. Transportation Network Profile (TNP), developed by the Volpe National Transportation Systems Center for the US Department of Transportation (USDOT) Bureau of Transportation Statistics (BTS). Nearly all transportation data follow this profile for network-related vector data.

Table 27 indicates which standard SDTS objects are required, optional or not permitted in TNP. The table reinforces the notion of a set of spatial predefined objects that make up SDTS and the TNP using a subset of these.

FGDC was previously felt to well underway in setting up LRS exchange formats, and it was reported that as the establishment of viable standards is a critical path in ITS implementation, research “was well established” (SDTS, 1997). A major three-day conference on the topic was held in September 1997. An argument was that further work needed to be done to extend the SDTS TNP to make useful for transportation practitioners (for example by adding “pseudo nodes”) and that “one model of doing business” was not adequate for the total set of transportation information communities (Lewis, 1997).

Since 1997 work on SDTS as a whole and on the TNP in particular seems to have lessened. A number of enhancements were required to make the TNP functional. The next section (Chapter/section 5.8.3) are some notes on the SDTS TNP relate to GDF and DIGEST.  

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9 This document and future updates are also available online through the SDTS web page, under Profiles at: http://mcmcweb.er.usgs.gov/sdts/
Table 27 SDTS TNP Definition

Source: NTS, 1996

<table>
<thead>
<tr>
<th>Object Representation Code</th>
<th>Require</th>
<th>Optional</th>
<th>Not permitted</th>
</tr>
</thead>
<tbody>
<tr>
<td>NP, NL, NE - Point, Label Point, Entity Point</td>
<td>X</td>
<td></td>
<td></td>
</tr>
<tr>
<td>NA - Area Point</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>NO - Node, planar</td>
<td></td>
<td>X (one of)</td>
<td></td>
</tr>
<tr>
<td>NN - Node, network</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LS- String</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>LE - Complete Chain</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LL - Areal Chain</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>LQ - Link</td>
<td></td>
<td>X (one of)</td>
<td></td>
</tr>
<tr>
<td>LW - Network chain, planar graph</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>LY - network chain, non-planar graph</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>AC, AE, AU, AB - All arcs</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>RA, RM, RS, RU - All rings</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>PG - G-polygon</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>PR - G-polygon (of rings)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>PC - GT-polygon (of chains)</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>PU - Universe polygon (of rings)</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>PW - Universe polygon (of chains)</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>PV - Void polygon (of rings)</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>PX - Void polygon (of chains)</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>GI, GJ, GK, GM - Raster objects</td>
<td></td>
<td>X</td>
<td></td>
</tr>
<tr>
<td>FF - composite</td>
<td></td>
<td>X</td>
<td></td>
</tr>
</tbody>
</table>


5.8.3 Institutional Standing: SDTS and GDF

Road network profile definition work in Europe and the US work has basically been progressed independently. GDF is already more advanced and more elaborated and detailed than SDTS (a more general (frame) standard). Thus, the use of US data standards have not really been an issue in Europe, i.e., there are no European articles, reports, etc. about this topic (as far as is currently known).

On the other hand, the concepts and the data model of GDF had been taken into consideration for the specification of the TVP of SDTS. The TVP has been developed at a time when both SDTS and GDF had become quite stable already. Therefore, GDF
could be used and played a considerable role (see e.g. SAE meeting minutes). Possibly, there might exist further US publications, other analysis documents, etc. on this issue.

Technical experts from Europe and US (and other countries) work on an "internationalized" version of GDF within global standardization committees (ISO/TC204 WG3). Some of the US delegates have been involved in the TVP work, too, e.g. from national map vendors such as ETAK. Inc., etc.

During the parallel development of map data transfer standards in the US and in Europe, some coordinating contacts had been established. The two key committees are:

1. **US: IVHS standards and protocols/SAE Map Database Standards Committee.**
   It worked on the Topological Vector Profile (TVP) (the current exact status of work is not known).
2. **Europe: EDRM2 project/CEN TC278 WG7 standardization committee.**
   It completed its work by issuing the European GDF 3.0 standard.

In the *International Standards Organization (ISO)* committee, North American and Asian requirement are particularly taken into account for the global GDF standardization. This potentially leads to real improvements and valuable extensions to GDF. Some recognized deficiencies in GDF could be overcome in this way, such as the quite restrictive model for administrative area hierarchies. It is argued however that it has turned out that the most fundamental concepts of GDF are still valid and did not need to be adapted.

ISO TC 204 WG 3 subgroup 3.1 is working on an international map database transfer standard for ITS based on an ISO update of GDF from CEN TC 278. The ISO version of GDF should have been available in 1998 *(was it).* GDF uses ISO 8211 at the physical implementation level, similar to SDTS and DIGEST.

The USGS held a workshop on SDTS in September 1997. Not much has happened on this subject since the workshop (USGS, 1997). To our knowledge, there has not been any new formal or informal activity to harmonize or compare GDF and SDTS. At the present time, there have not been any new developments at the international standards level (e.g., ISO) among TC 211 and TC 204 to reconcile international road data model standards. This may happen in the future.

To date, the ITS community at Oak Ridge are interested in this GDF - SDTS subject and a possible ITS profile of SDTS. There is also a SAE Map Database Committee (ETAK, NavTech, GM) that uses GDF. It does not have any strong requirements to harmonize with SDTS at this time.

At the GIS-T Symposium in 1997 in Utah, Bruce Spear of USDOT/ BTS at that time, discussed a project for the NSDI Framework Road Data Model Standard and mentioned a number of related standards that may be integrated with the project, including GDF, DIGEST, SDTS-TNP, and a proposed Transportation Data Content Standard. Information from Bruce indicates that the adoption of a standard road data model may lead to resumption of SDTS TNP development and its possible harmonization with GDF.

The Transportation Profile(s) (from the 1997 Profile information on the SDTS web site) includes:
1. Current Transportation Network Profile (TNP)
2. Proposed complete transportation transfer profile
3. Proposed ITS profile with sub-profiles.

The intended use of the current and proposed transportation profiles of SDTS are all designed to transfer and archive digital Geospatial data about transportation networks (e.g., roadways, railways, navigable waterways, transit systems), transportation facilities, and related events and features.

1. \textit{TNP}: The TNP is designed to allow the seamless representation of overpassing roadways using spatial primitives that need not be broken at overpasses and underpasses. To accommodate this, TNP data is not limited to a planar graph at the basic geometry element level. "Chain to node" relationships are the only required topological relationships between spatial primitives. Areas are not required. The primary SDTS objects are network chains, nodes, and composite objects (used for routes).

Some sample railway data in SDTS-TNP is available. Future use of the TNP by the US DOT for data distribution and data exchange will be considered after reconciliation of the TNP with the proposed SDTS ITS (GDF) profile, and reconciliation with the a proposed transportation profile to SDTS that supports linear referencing and is based on a complete enterprise GIS-T data model.

2. \textit{Complete Transportation Profile}: The proposed, more complete, transportation transfer profile to SDTS will based on an enterprise GIS-T data model from the recent work of Ken Dueker and Al Butler (1997). One aspect of this profile is more support for the linear location referencing of both tangible objects and characteristics from the earlier LRS data model research coordinated by Alan Vonderohe and refined in the ISTEA Pooled Fund work of David Fletcher and associates. For transportation data, SDTS needs to "provide an attribute-centric way to transfer transportation system characteristics independently of cartography" [from Dueker & Butler, 1997].

The enterprise GIS-T model supports multiple, independent cartographic representations, e.g., bridge geometry as points or point events at low resolution and as strings or linear events at high resolution. It supports variable linear feature segmentation as an alternative to rigid segmentation. New or modified SDTS terms are included, with a greater distinct on between (i) geographic or real-world references and locations and (ii) cartographic references and locations for map related CAD and GIS graphic elements. New linear datum objects include anchor points, anchor sections, and reference points. The use of a "transportation feature" with a permanent, unique identifier within a jurisdiction is included. There is advanced support for names. Junctions can be sub typed as intersections, interchanges, overpasses, intermodal connections, and intersections with boundaries; and they can be related to points at small scales and strings or interchange drawings at large scales. These junctions can be linked to information for traffic control, turn
possibilities, overpass loads, and underpass clearances. The Dueker/Butler model also provides support street addresses as for of linear referencing.

3. **ITS Profile:** An Intelligent Transportation Systems (ITS) profile to SDTS, or a Graphic Data Files (GDF) profile to SDTS, has been proposed by the ITS community in the U.S. (ITS America, NavTech, ETAK, AAA, Ford, Oak Ridge, SAE, etc.). The ITS profile to SDTS will probably be based on GDF, but there is a small chance that it could be non-GDF.

In a 1994 meeting, the IVHS America (now, ITS America) Standards and Protocols Subcommittee on Map Databases and Information Systems developed requirements for a GDF profile to SDTS. These requirements included possible specific sub-profiles based on ITS business areas, including Advanced Public Transportation Systems (APTS) (Watje & Okunieff, 1995), Commercial Vehicle Operations (CVO), and Advanced Vehicle Control Systems (AVCS). The APTS sub-profile to SDTS was also suggested as a transit sub profile to the TNP.

The FGDC Ground Transportation Subcommittee (GTS) and the US DOT Bureau of Transportation Statistics (BTS) were the primary sponsors of the TNP, with development work done at the Volpe National Transportation Systems Center. Additional information is available online at the BTS web site or the FGDC Ground Transportation Subcommittee (GTS) web site. The FGDC GTS is also very interested in GDF-based transfer standard with more linear location referencing support.

4. **ITS America, Oak Ridge National Labs:** They are involved with the ITS profile. A SDTS TNP Encoding Software has been developed at the US DOT Volpe National Transportation Systems Center, Cambridge, Massachusetts. Information is available at the FGDC GTS web site. SDTS TNP, as well as SDTS TVP, are supported by the GeoMorph conversion tool (developed by Application Software Technologies, Inc.).

GDF, along with SDTS, DIGEST, and similar exchange standards have been suggested as ISO standards. Some reconciliation among standards may be required by ISO.

The proposed ITS (GDF) profile to SDTS fits into this harmonization effort. SDTS is a configurable standard so it can be made to accommodate the models of other standards such as the feature-based models of GDF and DIGEST/VPF. Because of the configurable nature and model independence of SDTS, it has been recommended as a "harmonizing agent" or "umbrella" for other standards. DIGEST should also be considered in this transportation discussion because it is now designated as a civilian transportation standard in Canada and as a general standard by the defense communities of many nations.

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The requirements and possibilities for one or two new transportation profiles to SDTS need to be clarified and documented.

It can be seen that uncertainty currently appears to hang over the above public sector led efforts. The next two sections reflect efforts by private consortia.

5.9 Object Management Group (OMG)

5.9.1 Goal

The goal or focus of OMG is “interoperability”. OMG believe as a ‘wider credo’ that “there will be no single, commercially available, widely recognized and standardized integration approach and framework”. OMG defines object management as software development that models the real world through representation of "objects." These objects are the encapsulation of the attributes, relationships and methods of software identifiable program components. They list object oriented (OO) technologies as including OO:

1. Methodology / design / analysis
2. Languages
3. User interfaces
4. Databases
5. Software
6. Distributed applications.

OMG marshals arguments that an approach based on object technology offers significant advantages. In particular, they point to the potential OO advantages of:

1. Reusability of components
2. Interoperability
3. Portability.

A key benefit of an object-oriented system is its ability to expand in functionality by extending existing components and adding new objects to the system. Object management it is purported results in faster application development, easier maintenance, enormous scalability and reusable software. However, As there were several “flavors” or approaches to doing OO, OMG has set itself to create a common OO framework that includes:

1. Terminology
2. Abstract framework or object model
3. Reference model (or architecture)
4. Common interfaces and protocols

The architecture is “scalable”. For example, it includes objects which are:

1. “Lightweight”, single-process
2. Multi-process
3. Network distributed
4. Widely distributed

CORBA - Common Object Request Broker Architecture – is the overall framework for objects interacting (that is, request/result). The Object Management Architecture (OMA) Guide summarizes the architecture with terms and definitions upon which all supporting interface specifications are based. (OMG, 1999).

OMG had put in place by the late 1990’s put in place much of the generic software “plumbing to achieve general high-level systems operability. OMG realized that it is necessary to achieve interoperability above the level of mere” mechanistic compatibility” – that was, at the level of the semantics employed in each vertical industry domain. They noted:

*Transportation systems employ a whole vocabulary of their own. Some if it is truly unique to transportation systems, some of it is shared in common with other businesses. There exist semantics that are specific to each mode of transportation, as well as those common to all types of transportation. If we are to achieve interoperability at the application component level, we must produce standards in our own transportation application domain, as well. The OMG has thus formed a Domain Technology Committee, which in turn has spawned many Domain Special Interest Groups (DSIGs) and Domain Task Forces (DTFs) covering domains as broad and diverse as finance, medicine, manufacturing, telecommunications, and transportation.*

A Domain Special Interest Group (SIG) was created for Transportation in 1996.

OMG has a process for gaining end- consensus on what are likely to be agreed as wider industry accepted standards. This process is initially competitive, then seeks consensus. The process works through:

1. The development of Request for Information (RFI)s
2. Industry Requests For Proposal (RFPs), and
3. Technology Adoption Specifications.

5.9.2 Technical Approach

The OMG Transportation SIG is stated to be, “dedicated to forming standards for interoperable, distributed component architectures for the full breadth of the transportation industry …… by building a transportation-specific superstructure or layer upon the standard component framework, distribution architecture, and distributed services provided by the OMG’s Platform Technology Committee already.” (OMG, 1997). The aim of this group was stated to be to facilitate the development of standard, interoperable, architectural components for transportation applications.

The Transportation DSIG Mission includes:

1. Promoting the development and use of transportation related systems that incorporate OMG specifications and technologies.
2. Identifying relevant standards, business objects, components, and technologies in the field of transportation, and disseminating this information to the OMG.
3. Working within the OMG committees and task forces to ensure that the ORB, CORBA services, CORBA facilities, Business Object and domain specifications are conducive to the needs of the transportation industry.
4. Recruiting additional Transportation DSIG membership from corporations in the transportation systems development community.
5. Establishing a global forum for the free exchange of distributed object systems development ideas amongst the various members of the transportation community and its partners.

The Transportation DSIG was initially set-up comprising of four sub-domains:

1. Air
2. Marine
3. Highway, and
4. Rail transport.

The intent is to create a fundamental infrastructure that will enable integration and optimization of transportation information systems in all four sub-domains, as well as the distributed components of systems wholly within each sub-domain. Figure 37 shows the intended architecture of transportation domain applications. In order to achieve the development of the standards suite, to be known collectively as CORBA Transport, it must go through the standard RFI/RFP process described above.

The DSIG produced an initial draft Transportation Domain Reference Model paper in 1997. In this some overall view of "transportation" was taken. The transportation community was realized to be a set of inter-relating transportation information communities (see Figure 46).

Figure 46 OMG Transportation Application
Figure 47 OMG View of Transportation Enterprise Community

Community Objective: To provide quality shipment services between all locations.
5.9.3 Institutional Standing

In summary, it may be stated:

1. OMG is focused at commercial, largely software-producing organizations
2. OMG is not practically "open" in its processes. For example:
   a) The documents referenced in this section are believed to not be generally available to the public. That is, you have to join OMG and given the fee structure, etc., it helps to be a large organization to do this. Individuals do not play.
   b) OMG (and OGC) meetings are held all over the world. If one cannot attend meetings, it is difficult to effectively contribute.
3. The applications looked at to date have been exclusively driven by available funding (e.g., military shipments, ITS, etc), as can be seen by reference to Figure 47. This is in comparison to “what is fundamentally required to create a underlying transportation architecture”. Work in the highway area has not progressed.

4. There appears to be some at least relative duplication of work between OMG and OGC and also other organizations described in this chapter.

5. Very few individuals who have attended an AASHTO meeting (i.e., transportation professionals) have attended an OMG or OGC meeting (i.e., IT professionals), or vice-versa.

Officially, OMG and OGC (next section) work in close liaison.

5.10 Open GIS Consortium

5.10.1 Goal

The Open GIS Consortium (OGC) has as its goal the development and provision of an architecture to promote interoperability – in contrast to OMG, spatial interoperability.

The definition of the core domain potentially provides certain Geospatial basics that the transportation community can potentially use. However, it is not currently proposed to deal in adequate detail with the specific elements that the transportation community uses (such as, “roads,” “routes,” and “corridors”). Even within one State DOTs, multiple definitions of “road,” “highway segment,” and “route” may exist. As a multi-disciplinary field, covering many aspects of life, transportation has much to gain from interoperability.

The OGC had already established a Telecommunications Technical Working Group (TWG). To address the business needs of the wider Transportation community, the OGC formed a Transportation TWG in 1997. This TWG was originally chaired by Simon Lewis and then by Steve Smythe of Microsoft. Attendance at such meetings, as with OMG often international, requires support of large organization.

In brief, the proposed purpose of the transportation TWG is to define the wider transportation domain business needs and propose extensions to the core OGC data model that will meet the interoperability needs of the transportation community. It was originally intended again to focus on clarifying the precise business needs of the transportation community by first defining transportation sub-communities. It was felt it may then be better to articulate more precisely transportation business differentiators when interacting with parallel industries undertaking network-based management and analysis.

The initial goal of the SIG was stated to “develop an understanding of the work and positions of the other groups, then to refine the abstract specification and initiate Working Groups for the adoption or design of appropriate APIs” (internal OGC documents).

The proposed scope of the Transportation SIG was to include all forms of travel and transportation where a position-aware mobile computing device accompanies the person and/or vehicle. This includes travel by people by foot, using non-motorized or motorized vehicles, animals, rail and road transport, vessels upon on in bodies of water and aircraft on the ground or in the air.
At the point the Transportation SIG was starting it was realized that it would not be starting from scratch. It could build on the considerable work already done in the US, Europe, Japan and Australia. It was felt that the rapidly developing mass market for car navigation - particularly in the US and Europe made it imperative that OGC was a prominent player in the field.

5.10.2 Technical Approach

The purpose of the Transportation SIG within the Core Task Force is to develop additions to the OpenGIS abstract specification to take into account the ongoing developments in transportation related technologies

5.10.2.1 Technical Foci

The four major areas initially proposed for OMG technical focus were:

1. Locational referencing
   a) Linear referencing systems
   b) Street Addressing Systems
   c) Other Descriptions of “where”
   d) Name Resolution
2. Temporal Representation
3. Modeling of Networks and Topological Relationships
4. Generalization and Aggregation
   a) Presentation
   b) Subnets
   c) Temporal

It was intended that there would be a lot of fertilization with the Telecom SIG. The technical scope will broaden to include proposals for APIs to meet needs/opportunities identified as work progresses.

5.10.2.2 Technical Standards Liaison

The work of the SIG was intended to liaise with work being done by other international standards organizations. These were identified as:

1. ISO TC 204 Transport Information and Control Systems (TICS).
   Activities there include:
   1) WG3 Referencing and Updating Procedure
   2) Geographic Data File - The definition of an application independent standard for interchange of TICS database
   3) Physical storage for TICS Database - The standard for the data models used for the storage of Vehicle Navigation and Travelers Information Systems database compiled from geographic data file.
   4) Location Referencing Procedure - This section of the standards specifies the location referencing procedures for the geographic database
5) Publishing Updates for Geographic Databases - This section of the standard will specify the formats and procedures for publishing updates of geographic database used in TICS applications.

2. WG 3 (Referencing and Updating procedure) and WG11 (Dynamic TICS Information).

3. ISO TC 211 (Geographic Information/Geomatics).
   Work areas include:
   1. WG1 Framework and reference model
   2. Support for
       - construction of transportation infrastructure
       - network analysis to be shared with the Telecom SIG

3. CEN TC 278 WG7 Geographic Road databases and Road Transport and Telematics. These databases include:
   - GDF
   - RADEF
   - RDS_TMC
   - Alert C, Alert +
   - GSM, GATS

5.10.3 Institutional Standing

After some strong focus 1997 to 1999, Microsoft and OGC seem to have currently put their transportation standards efforts onto a slower track. The exact situation is not fully clear at the time of writing. This indicates the possible difficulty of generating national standards which may be at the commercial whim of one or another larger market vendor.

5.11 Chapter Summary and Conclusions

5.11.1 Progress Achieved

This chapter undertook a compilation of the different road data models that may be used in association with LRS. A criticism of this coverage here may be that a very clear distinction was not made between those that explicitly posit themselves as:

1. LRS encoding schemas (more clearly, the 20-27(2) model), and,
2. Those that are primarily centerline network representation coding standards.

It was seen in the coverage here that some of the models are directly focused on LRS (such as the NHCRP 20-27(2) model, others currently include simple LRS components (such as GDF and the BTS framework).

It is believed that the coverage here is the first time a formulation such as been formulation has been compiled. Clearly, the analysis needs to be extended and deepened.
Further analysis of some of these models is made in Chapter 8.

5.11.2 Ten Key Observations

1. No winner: No one general model has gained more universal popularity and acceptance across DOTs, vendors, and government organizations.

2. Organization Preferences: DOTs seem to favor the Vonderohe approach, local agencies were important in creating the BTS standard, the federal government has supported SDTS and the ITS community the ITS Datum. GDF is popular with data vendors.

3. Low Current Development Level: While there was a spate of activity on road data models in the mid-1990's, the current position with several of the models or formats is unclear. At least some efforts deem to have at least relatively faltered.

4. GDF Role: While popular in the US with data vendors, GDF has gained popularity in Europe (where it originates). While a likely standard in the US, it is probably fair (i.e., realistic) to say its full appropriateness in a US and North American setting has not yet been made fully documented or made fully clear.

5. SDTS-GDF: There have been a number of efforts to investigate the integration of SDTS and GDF, but, in short, these seem not to have been actively pushed recently.

6. NHCRP 20-27(2) Model: This would seem to offer the greatest potential to further develop. The use of anchor points and sections maybe a work of gaining cross model interchange.

7. No One model Fits All: The above may simply reflect that no one model truly equally suits all transportation purposes. There are likely to be constraints in the use of all of the models/formats for some purposes.

8. Documentation: The GDF, SDTS and BTS model/formats are well documented, the others less well. All have lacked from the availability of a manual that provides wider field guidance to using and setting up road data models and LRS. The NHCRP model in particular does not provide any detailed advice on dealing with LRS field issues or how in particular in any depth how to apply the model itself in the field.

9. Further Research: This is required in the overlap and integration of these models.

10. Further Progress. It seems that further progress will not be likely on the integration of the models without some top-down national governmental push.
5.11.3 Main Conclusions

The transportation community and potential users of road data models have challenges to make decisions in the face of uncertainty. Just some of the overlapping conceptual possibilities include the following:

1. **"Wait Approach"**: This involves waiting for any one of several possible developments for several possible developments (but none of which may in fact occur). This approach would involve wait, watch, and reacting to further:
   a. Standards developments at the ISO level among SDTS, GDF, and DIGEST/VPF (discussed later).
   b. SDTS developments, e.g., a more inclusive object-based profile (discussed later) that may be related to an archive standard for OpenGIS (OGC). Wait for further momentum or requirements from FGDC, e.g., for framework distribution and archive.
   c. Requirements and demand from major data producers and GIS vendors.
   d. Sufficient user dissatisfaction with current use of format translators for spatial data exchange. Use SDTS-TVP (see, D. Schmidt, 1997 thesis) for transportation data exchange while waiting.

2. **TNP Approach**: Replace or modify the TNP into two transportation standards. This would be:
   a. A GDF profile to SDTS to accommodate the ITS community, and
   b. An enterprise GIS-T profile.

Doing GDF, GIS-T, and SDTS all at once may (or, may not) be too large an initial task. An ITS profile may be a first step, with the intention to include GIS-T and LRS requirements as a second step after learning from the first step.

3. **Two-step GDF-ITS Approach**: This involves:
   a. Define an overall architecture or approach, then
   b. Develop a single, combined GIS-T and GDF-based ITS profile to SDTS as "The Transportation Profile to SDTS."

This will help avoid rendering any initial components obsolete.

4. **OGC Approach**: Work with developers of a proposed object-based profile to SDTS and with the new OGC (OpenGIS) Transportation Domain Technical Working Group to include complete transportation and GDF requirements in the object-based profile.
There are various 'pros and cons' for each of these alternatives. These alternatives were discussed at the SDTS workshop in September 1997, but seem to have not been much progressed or more formally by the transportation community at large since then.

*Basic research is what I am doing when I don't know what I'm doing.*

Wernher von Braun
5.12 Chapter References


Federal Geographic Data Committee. Requirements for the SDTS TNP. Version 1.1 BTS or FGDC GTS web sites. February 1, 1996.


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6 Field Definition of LRS: The Case Studies

*Experience keeps a dear school, but fools will learn in no other.*
Benjamin Franklin

*Things done without example, in their issue
Are to be fear’d. Have you a precedent
Of this Commission?*
Act 1, Scene 2. King Henry VIII.
William Shakespeare.

6.1 Chapter Purpose

Primary goal of this thesis is to provide information that will aid work on:

1. Describe issues that are encountered with existing LRS use
2. Potentially refine the use of existing LRSs
3. Thence, if appropriate, some development of conceptual bases for LRS.

It had been noted (in particular, Chapters 2 and 3) that spatial data is inherently complex. It has many field variations and uncertainties, even for simple cases. This includes with the definition of road networks, on which LRS sit.

This chapter with this premise in mind reviews LRS implementation and issues in more detail, based on four case study DOT’s. As indicated in the second quote provided above, “precedent for this commission” was felt a necessary base for not only the consideration provided in this thesis for wider transportation field consideration of LRS as a whole. This chapter in a number of ways is the focal point of the research undertaken here.

A spectrum of ten linear referencing implementation issues is explored in more detail. There are in fact many issues that could be addressed but the nine selected represent an important cross-section of key issues. A tenth issue, the representation of time, is also considered within this thesis. This chapter will demonstrate some of the variety of spatial experience even in the basic simple linear or network form.

The LRS issues considered here are:

1. Coding traversal identifiers
2. Use of separate traversals for each travel direction
3. Special cases for defining traversals. Twelve special cases are reviewed. These are:
   a. Divided highways
   b. Ramps and approaches
   c. Non-contiguous traversals
   d. Overlapping traversals, etc.
e. One-way pairs
f. Layered or tiered roadways
g. Service roads
h. Individual lanes (including HOV lanes)
i. Associated facilities (e.g., truck runoffs, etc)
j. Rotaries
k. Cul-de-sacs
l. Proposed roadways

4. Use of mileage equations
5. Location accuracy
6. Linear referencing for local roads
7. Determining location and distance: field and office practices. Three issues are focused on here. These are:
   a. Use of mileposts and reference posts
   b. Determination of traversal/Section lengths
   c. Determination of event locations
8. Linear LRS maintenance and quality control
9. Multimodal Integration

The tenth issue – temporal representation is considered in a subsequent chapter. The case studies indicated that these issues represent the key concerns for LRS in the field. A considerable portion of this thesis is given to these areas. It is believed that the review presented here is as comprehensive as has been prepared to date. Nevertheless, the review here is still summary in format. Considerations of space, not wishing to overburden the reader with too much operational detail, and sufficient example being drawing from the material already presented, were reasons for the balance chosen. A whole chapter could have easily been written on LRS considerations of for example

1. Traversals: special cases for defining traversals”, or
2. Ramps (which as summarized, is a small sub-section of this chapter).

The general layout of each selected LRS topic within this chapter is as follows:

1. Theoretical and Field Considerations
2. Real World Implementations
3. Discussion of Case
4. Design Implications

However, while this general outline is followed generally, it is modified to best fit the material.

The analysis starts by a top-level overview of the four case studies.

In implementation terms, though in some ways more elemental the chapter reflects basic research is the practical core of the thesis.
6.2 Introduction to Case Studies

This section introduces and overviews the LRS case studies. The detail of the material analyzing specific LRS points from the Case Studies is presented in the following sections. For analysis purposes the material in the next chapter has been divided by topic or technical issue for the benefit of comparison of the results of the case studies. This section provided a brief introduction to the case studies.

The questionnaire set up for study use is contained in Appendix D. The full questionnaire results are available for all the DOTs but not included in appendices for reasons of length; that for Missouri DOT is included in Appendix E. The information provided here is believed to be correct to at least 1998, but may have been subsequently updated. Where this is known to have occurred, note is so made.

As previously indicated, the heart of every linear LRS is its traversal organization scheme. Although a framework for traversal organization was introduced in section 4.2.3, this section provides an overview of how each case study participant implemented their linear LRS. Table 28 offers a general comparison between the four LRS case studies.

<table>
<thead>
<tr>
<th>Principal linear referencing method</th>
<th>ITD</th>
<th>MoDOT</th>
<th>PennDOT</th>
<th>WSDOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Control section (incorporating historical changes)</td>
<td>base-offset (named route/milepoint)</td>
<td>control section (roughly equal length)</td>
<td>base-offset (named route/milepoint)</td>
<td></td>
</tr>
<tr>
<td>Years in use</td>
<td>20</td>
<td>1</td>
<td>10</td>
<td>50</td>
</tr>
<tr>
<td>Number of linear referencing systems in use</td>
<td>1</td>
<td>2 (includes 1 legacy system)</td>
<td>1</td>
<td>2</td>
</tr>
<tr>
<td>Extent of roadways</td>
<td>Minor collectors and above, with rest areas</td>
<td>All public roadways, some private drives</td>
<td>State routes (no local, county or city roads)</td>
<td>State system (no local, county or city roads)</td>
</tr>
<tr>
<td>Ramps included</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Treatment of divided highways</td>
<td>Single control section (some exceptions where lengths differ)</td>
<td>Separate traversal (‘Travelway’) for each direction of travel</td>
<td>Separate traversal for each direction of travel, both oriented in mainline direction</td>
<td>Separate traversal for each direction of travel</td>
</tr>
<tr>
<td>Mileage equations</td>
<td>Yes</td>
<td>No</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>GIS</td>
<td>Intergraph/MGE</td>
<td>Arc/Info</td>
<td>Intergraph/MGE</td>
<td>Arc/Info</td>
</tr>
</tbody>
</table>

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Each of the four case studies is briefly summarized below. A more detailed comparative analysis is provided on a topic-by-topic basis in sections 4 and 5 below, including how different types of roadways are handled and their relationship to the underlying network centerlines.

6.2.1 Idaho Transportation Department (ITD)

ITD has used a single, enterprise LRS for nearly 20 years. This is called the MACS/ROSE (Milepost and Coded Segment/Road Segment) system. A mainframe application is used to manage the LRS control files and integrate key event databases. The LRS is based on the concept of Segments, which are underlying control sections to which all linear data are referenced (by milepoints and dates).

MACS/ROSE includes a number of distinct (and some unique) features:

1. Traversals correspond to Segments, which are defined based on the physical roadway, and thus are not based on any roadway attributes. The Segment code is a random 6-digit alphanumeric identifier.
2. Time is an integral part of the LRS. Unique segments are identified by a composite key, including a Segment code, begin/end milepoints, and effective and expiration dates.
3. The system inherently manages historical data, by use of effective and expiration dates in the LRS control files and in event tables.
4. When the original system was established (1978), single Segments generally corresponded to numbered highways, and could be hundreds of miles long. Currently, some Segments are more fragmented, due to updates to the system (realignments, changes to highway designations and, to a lesser extent, re-measurements).
5. Milepoint control files maintain known milepoint values at various features along Segments.
6. Route control files group Segments (and portions of Segments) into routes that correspond to numbered highways, federal aid funding categories, scenic/historic byways, etc.

The MACS/ROSE system was originally created with “intelligence” built into the coding of its Segments. That is, the original Segment codes corresponded to highways as numbered in the field. However, it was soon recognized that this offered no advantage over a legacy ‘route and milepoint’ system that MACS replaced. Therefore, ‘intelligent’ Segment codes were replaced by arbitrary Segment codes tied to physical roadway sections that remain constant regardless of changes to highway route numbers.

The MACS/ROSE unit of the GIS Section, Planning Division, has full responsibility for the MACS/ROSE enterprise LRS. Responsibilities include assignment of Segment codes, data input and updates, assuring system integrity, notifying users of system updates, providing user access to the system (at different levels), developing custom reports, point of contact for system information, developing user guides, and recommending system policies and enhancements. The MACS system was developed in-house, as a refinement of an existing LRS, using database design principles typical of the time (1975-77). NCHRP Synthesis 21 (Baker and Blessing, 1974) was instrumental in the refinement of ITD’s existing LRS and the design of MACS/ROSE.
The Intergraph/MGE GIS has been used for a rudimentary implementation of the MACS/ROSE LRS, using an Informix database. The implementation was done primarily to demonstrate the potential use of GIS. The base map has not been kept fully up to date, but is used to generate custom maps on a case-by-case basis, generally using customized data sets provided to the GIS section. Only current Segments are included in the GIS base map; effective and expiration dates have not been incorporated, which poses a problem for historical events. For example, a Segment’s milepoints might be revised due to realignment. The old Segment would be expired, and a new one added with a new effective date. An accident coded as falling on the old Segment might now be displayed by the GIS along the realigned Segment.

There are a number of minor enhancements desired of the MACS/ROSE system. A business plan is currently being formalized to make these revisions. For example, system refinements could enable users to reference common highway numbers and names for data input and reporting, rather than the current practice of locating roadway attributes by reference to Segment codes (which are random identifiers).

6.2.2 Missouri Department of Transportation (MoDOT)

MODOT is developing a Transportation Management System (TMS), an automated system that includes a collection of applications to integrate multiple management systems. In Phase 1, it consists of bridge, pavement, safety, congestion, traffic monitoring and inter-modal inventory. TMS will serve as the MoDOT enterprise transportation database, with the following goals:

1. Incorporate legacy databases through custom loading routines
2. Provide data access and maintenance tools to other offices
3. Enable query and reporting through a common interface (Impromptu and ArcView)
4. Move toward migration of systems to be directly incorporated in the enterprise database.

At the heart of the TMS is the Travelways system, providing a standard location referencing system and methods for locating the events and features of interest to MoDOT. Traversals correspond to numbered or named routes as signed in the field.

The Travelways system supports several location referencing methods, including:

1. Log units (milepoints or kilometer points, based on an enterprise linear referencing system)
2. Distance from a known point along a traversal
3. GPS coordinates (not currently used, but supported for future use)
4. Address geocoding (based on TIGER addresses).

Several special features of the Travelways system include:

1. Extensible to all modes of travel along linear features (roadways, railways, waterways, airways, etc.)
2. Separate traversals defined for both directions of travel on all bi-directional Travelways
3. Complete management of historical data
4. Transaction-based management within a relational database (Oracle), fully integrated with a GIS base map
5. Common access to the centrally maintained enterprise system by all MoDOT offices
6. Integrated management of core roadway attributes (e.g., functional class, etc.).

To aid in the transition to the Travelways system, a previously used LRS (the ‘old system’) is currently supported within the TMS application. This ‘old system’ is only supported to aid in the one-time conversion of data from legacy systems to TMS and to aid in interfacing from legacy systems to TMS until the legacy systems are replaced. It is considered a strong point to develop and support a single, enterprise-wide LRS, rather than accommodating multiple LRSs and translations between them.

The ‘old system’ had a number of limitations which, given newly available technology, warranted development of a completely new enterprise LRS. These limitations included, for example:

1. The older mainframe system maintained three concurrent log systems (‘basic’, ‘geometric’ and ‘current’), and some offices and Districts effectively maintained their own LRSs (generally with differences in milepoints, not routes). Updates were not synchronized between different offices, so that they each maintained different log miles.
2. There was no consistent management of historical data.
3. Interchanges were not fully represented (routes met at a single ‘point’, regardless of divided highways), so that all accidents or signs at an interchange would be coded to the same point.
4. Where routes left and re-entered a county, the milepoints would restart where they left off, creating two points on a route with the same milepoint (the same was true for alternate routes on overlapping route sections).
5. Milepoints were reset to zero where a highway changed between divided and undivided.

As stated in one interview, data analysis in the old system could be “80% determining and rectifying location, and 20% analysis.”

The new system improves on these limitations and provides for systematic integration of all management systems. Centralized management of updates to the system will simplify record keeping by individual offices. As well, the Travelways LRS will be completely coded in the MODOT GIS base map, and direct query of the database will be provided through a GIS (ArcView) interface.

Although the TMS is currently in development, key functionality has been demonstrated through a prototype. The system is the result of two years of analysis work followed by approximately 15 months of concentrated development (as of November 1997). The Office of Transportation Management Systems (OTMS) is responsible for all transportation management information systems. This includes the GIS and the Travelways sections. The Travelways system was developed using the Composer CASE tool (Sterling Software, previously owned by Texas Instruments). Composer was used to develop the logical data model, as well as applications that enforce the data model integrity and embedded business rules.
WSDOT uses the Transportation Information and Planning Support system (TRIPS), a mainframe application, to manage the Department’s core transportation data. Within TRIPS, the State Highway Log contains roadway data and mileage statistics for all State Highways (over 7000 miles). It is designed to provide a record of current highway system information and a source for computing distances between major points.

The State Highway Log includes the following key elements:

1. The highway network maintained by WSDOT is referred to as the State Route System. Each State Route is treated as a continuous traversal. This comprises increasing and decreasing routes (traversals) representing each direction of travel.
2. Route system IDs are stored as twelve-character codes with mainlines identified by the basic State Route number (‘002’, for example).
3. There are the two main linear referencing methods used by WSDOT:
   - The State Route Milepost (SRMP) method uses reference points along routes, and has jumps and gaps in the route mileposts due to changes to road geometry over time
   - The Accumulated Route Mileage (ARM) method records the current, actual distance from the beginning of each individual route.
4. The State Highway Log contains conversion equations to cross-reference SRMP and ARM values.
5. Field data collection is referenced to the SRMP, although actual measurement may be from a permanent structure such as a bridge. Data collection methods include data collection vans with DMI and videolog.
6. Field measurements are generally taken to the nearest 1/100-mile, i.e., 52 ft. (consistent with a mapping scale accuracy of 1:32,000).
7. Transportation data are stored by State Route, Increasing or Decreasing route system, Section ID and SRMP value.
8. The TRIPS System Realignment File tracks all changes by date and by route. When realignment occurs the accumulated route mile value (ARM) changes, but the SRMP remains the same. A new ARM value is added to the beginning of the realigned section and all measures after this point are adjusted.

In the SRMP method, Sections are defined between convenient measurement locations, such as intersections and bridges. Sections are generally less than one mile long. Some roadway characteristics are associated with Sections, which are indirectly linearly referenced by the begin and end mileposts of each Section along its respective route. In addition to the SRMP and ARM referencing methods, other minor methods in use throughout the Department include control sections, HPMS links, engineering stations, addresses, and simple text description (“the I-90 project”).

A GIS application was developed to integrate the State Highway Log with GIS base map to map and display transportation data. The application is known as MADOG (Mapping, Analysis and Display Of Geographic data). Its implementation is a specific extension of the capabilities of the State Highway Log in GIS. Developed in the ArcView GIS, MADOG extends the capabilities of the WSDOT LRS in a number of ways:
1. Provides a graphical user interface for the query, display and mapping of transportation data
2. Add routes for ramps to the two existing referencing methods
3. Provides a visual means of viewing the locations of SRMP and ARM values
4. Enables referencing of data by linear referencing on the map, which can then be stored in MADOG (e.g., accident locations)
5. Stores events either at a point or along a line - dynamic segmentation automatically displays events along routes
6. Integrates other GIS data sets such as hydrology, administrative boundaries, local roads, etc.

The State Highway Log and MADOG systems are independent of each other. MADOG is a GIS query and display tool that utilizes State Highway Log data but is not used for data management or update.

The TRIPS system contains many other data sets provided by District and Headquarter sources. This is not directly linked to the State Highway Log but an interface can be provided to Divisions or Districts who wish to correlate pavement data, etc. There is no automated method for performing the correlation at this time. However, TRIPS system is being migrated from ADABAS mainframe database to SQL Server RDBMS, and the data model design will allow State Highway Log data to be integrated with other data sets. This new system is called TARIS (Traffic Accident and Roadway Information System) and should been completely implemented by the end of 1998.

The State Highway Log is managed by the Transportation Data Office, part of the Planning and Programming Service Center (PPSC). The Transportation Surveys Section of PPSC is responsible for updating and maintaining the roadway portion of the TRIPS system. The Roadway Data Section of the Planning and Programming Service Center provides roadway geometrics and attributes for reports.

GIS activities are distributed throughout the Department. The Geographic Services Office of the PPSC implemented the LRS in GIS and developed the MADOG application. Application development is the primary responsibility of the Management Information Systems (MIS). GIS development is coordinated by a GIS Implementation Team made up of staff from various units throughout the Department.

Issues related to linear referencing currently under consideration by WSDOT include:

1. Validation of LRS locations using GPS
2. Inventory of attributes along the network using GPS and DMI
3. Updating the LRS in the GIS
4. Resolving temporal issues
5. Integrating other jurisdictions' referencing methods
6. Restructuring the LRS and attribute data into a relational database, and
7. Developing a data dictionary.

6.2.4 Pennsylvania Department of Transportation (PennDOT)

PennDOT manages approximately 41,000 miles of State Routes (SR). There are 25,000 bridges (structures whose span is eight feet or greater) in the system and more than 47,000 records in the
SR geographic information system (GIS) segment base. The surface transportation system is administered through 11 district offices overseeing 67 counties.

Prior to 1986 at least a minimum of 12 identified LRMs were maintained for state operations; for example, railroad crossings, HPMS, maintenance management, pavement condition surveys, and traffic monitoring. Each of these systems required some use of the others and there was a snowballing time lag through the entire update procedure. A task force (5-10 individuals) was formed to integrate all systems into a single function that was computer compatible and did not require the use of mileage equations. Once a consensus system and business plan was developed, a small pilot program was implemented to forge procedures and identify implementation problems.

In 1986, all roadway transportation, maintenance, operations, safety, planning, and all related functions were placed beneath a single linear referencing system titled the Pennsylvania Roadway Management System (RMS). This marked the transition from the legacy system of old Legislative Routes to State Routes (SRs), a transition necessary to bring all users beneath a single LRS that was fully manageable in a computerized environment.

The resulting LRS utilizes control sections uniquely identified by a hierarchical coding scheme (county code, State Route number and segment code), with events located at milepoints along the control sections. Individual sections are approximately 0.5 miles in length, and are identified in the field by reference posts (or ‘field information paddles’). As the network evolves, the reference posts are relocated as needed.

All state routes have been implemented with control sections coded in the Intergraph/MGE GIS base map (based on USGS 1:24,000 topographic maps). As a rule, the GIS does not carry ramps unless the USGS quad sheet illustrates the same (there has been little customer demand for products with ramps displayed). A well-defined business process assures coordination of updates between the GIS section and the mainframe linear LRS control tables.

Of particular note is the overall stability of the single LRS and its impact on coordinated operations among diverse functions. Thirteen distance measuring instrument (DMI) vans routinely collect field data to verify existing features and add new features during a four-year update cycle. PennDOT is thus in their third revision cycle and nearly all field uncertainties have been removed. As the instrumented vans collect information, new data are merged nightly in mainframe batch loads and integrated with a straight-line diagram (SLD) and section/offset LRM. A system of field calibration points helps to anchor traversal sections to minimize GIS event floating. The PennDOT GIS section receives regular reports of new, deleted, or changed features, at which time the Intergraph-based GIS data is updated.

PennDOT’s Bureau of Maintenance and Operations is responsible for the computer system in which the LRS is stored, while the Bureau of Planning and Research is responsible for GIS. Planning and Research is the PennDOT’s research program, managing academic partnerships and the local technical assistance program, transportation systems information, highway travel data collection and performance statistics, cartographic products including all official transportation systems, maps, and geographic information systems development.

The following chapters describe and analyze various aspects of linear referencing using the four case studies as specific references.
6.2.5  Case Study DOT GIS Development and Use

At one time, accurate digital data were not readily available in the state DOTs and personnel lacked the necessary training to efficiently build a GIS database. A great deal of digital data is now available. Further, building or upgrading map lines is possible through the attachment of differential GPS to videolog or data collection vans.

Table 29 compares the use of GIS between the four case studies as well as some of their applications, followed by a brief description of each case study's use of GIS.

**Idaho Transportation Department:** ITD uses Intergraph/MGE for a rudimentary implementation of their MACS/ROSE LRS coupled to an Informix database. The implementation was done several years ago, primarily to demonstrate the potential use of GIS. The base map has not been kept fully up to date, but is used to generate custom maps on a case-by-case basis, generally using customized data sets provided to the GIS section. Only current Segments are included in the GIS base map. The structure of effective and expiration dates for building historical traversals has not been incorporated. This has presented a few problems, such as having an accident coded in an expired Segment incorrectly displayed by the GIS along the realigned Segment.

**Missouri DOT:** MoDOT's GIS base map is primarily derived from TIGER data, with the geometry of divided highways, interchanges and other special features added as needed. Some centerline data have been integrated from more accurate sources (e.g., St. Louis roads based on GPS data). Routes are being coded manually and with semi-automated tools. Beginning and ending measures (based on logbooks from the 'old system') are being entered for each arc. Full quality control includes traversal calibration, roadway-naming alignment following conflation, and manual spot-checking. By fully integrating the GIS data with the Oracle database, the update process for the Travelways system will be simplified while assuring greater data integrity. The GIS implementation has also enabled data visualization of both legacy data and newly integrated data that was not previously possible on the enterprise scale. Current plans are for 100 GIS workstations to be rolled out to central and District offices for use with the system.

**Washington State DOT:** WSDOT built their GIS from rectified Microstation CAD imported into ARC/INFO. The CAD linework was cleaned, topology added, and attributes for SR ID, ARM begin and end, and direction (increasing/decreasing) attached. Traversal systems were next established using ARC/INFO MAKEROUTE. The coverages were then un-projected into geographic coordinates (latitude/longitude) at three levels – county, region and state LRSs. The MADOG application, comprising AVENUE scripts and the ArcView GUI, accesses the coverages with the routes. Point and linear event data can be referenced by the LRS, e.g., GPS data. Distribution to the Districts and Headquarter users is through ArcView.

**Pennsylvania DOT:** When PennDOT built their GIS, the map base was hand digitized from 1:24 k quadrangle maps. In fact the base map is synchronized with the 1:24 k USGS map series, and only after a new road actually appear on the USGS map does PennDOT formally add the roadway to their GIS. The GIS section also carries additional information on dams, hydrology, types of roadway routes, and US traffic and ramps. As a rule, the GIS data does not include ramps unless the USGS quad sheet illustrates the same. Generally, there has been little GIS need or customer demand for products with ramps illustrated. GIS section has always provided hardcopy maps of state routes and other segment information; and also made LRS available in a usable form through an ability to display data. The greatest success story followed as the district offices came online with GIS. Once the districts had full access to GIS themselves, the demands for standard
### Table 29 General Comparison of Case Study Use of GIS

<table>
<thead>
<tr>
<th>Use of GIS</th>
<th>ITD</th>
<th>MoDOT</th>
<th>PennDOT</th>
<th>WSDOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GIS used</td>
<td>MGE</td>
<td>Arc/Info</td>
<td>MGE</td>
<td>Arc/Info</td>
</tr>
<tr>
<td>Source map scale</td>
<td>1:100 k</td>
<td>1:100 k</td>
<td>1:24 k</td>
<td>1:24 k</td>
</tr>
<tr>
<td>General accuracy</td>
<td>Not assessed</td>
<td>Not assessed</td>
<td>40 ft</td>
<td>40 ft</td>
</tr>
<tr>
<td>Map source</td>
<td>USGS maps</td>
<td>TIGER</td>
<td>USGS maps</td>
<td>USGS maps</td>
</tr>
<tr>
<td>GIS used for data display &amp; mapping</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Can GIS be queried to build reports</td>
<td>Not in business process</td>
<td>In development</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Point at a GIS and get a linear measure</td>
<td>No</td>
<td>In development</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Quality control of GIS data</td>
<td>None established</td>
<td>Automatic process</td>
<td>Formal hand process</td>
<td>None established</td>
</tr>
<tr>
<td>Integration and analysis of different event tables</td>
<td>No</td>
<td>Through ITIS</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Conversion capabilities between multiple linear referencing methods</td>
<td>Not needed</td>
<td>Yes</td>
<td>Not needed</td>
<td>Yes through MADOG</td>
</tr>
<tr>
<td>GIS integrated with videolog</td>
<td>No</td>
<td>In development</td>
<td>In process</td>
<td>Yes</td>
</tr>
<tr>
<td>Do linear LRS and GIS lengths differ?</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
</tbody>
</table>
A unique, random number is then used as an internal identifier for each Travelway to assure integrity of the physical Transportation Management System (TMS) database. If a roadway name or any other component of the traversal ID is changed, the internal identifier remains the same. A ‘name history’ table in the Travelways system keeps track of any changes to the traversal logical IDs. The unique internal identifier also corresponds to the traversal (‘route’) identifier in the GIS.

TMS on-line applications will allow users to choose Travelways by selecting the logical names from lists. For data conversions and interfaces to the legacy system, the legacy data must include the correct designation and names (direction can be determined/assumed as primary if the other two items are given).

Note that for external users (outside of the Missouri TMS), this system requires that the lengthy logical identifiers be used. As an alternative, systems or applications independent of TMS could make use of the same internal identifiers (and tools for their use) as provided in TMS.

**Idaho Transportation Department:** A traversal in the ITD LRS corresponds to a MACS/ROSE Segment, uniquely defined by a 6-digit random Segment ID. The definition of traversals becomes more complicated when historical data are considered, as will be discussed in section 7.4.

**Pennsylvania DOT:** PennDOT utilizes control sections that are uniquely identified by a hierarchical coding scheme. This scheme includes a county code, State Route number and segment code. For example, section ‘50SR001.S01’, where:

- 50 = County code
- SR = State Route
- 001 = State Route Number
- 01 = Section number
- S01 = Segment number

**Washington State DOT:** Transportation data are stored by State Route (increasing or decreasing), Section ID and State Route Milepost (SRMP) value. Traversals are therefore defined by “Sections”. The State Route ID’s are stored as 12 character codes comprised of:

1. A State Route number (3 digits)
2. A ‘roadway type’ (2-character code for ramp, spur, etc.), and
3. A ‘roadway qualifier’ (6 characters) to distinguish multiple roadway types on the same route.

Together with the State Route number, these descriptors uniquely identify any piece of highway in the state. The ‘roadway type’ includes a direction indicator (increasing or decreasing) for selected roadway types, as shown in Table 30. The roadway qualifier may be a street name, the name of a ferry ship, or a milepoint where a spur leaves a mainline. Thus the traversal IDs might be subject to change if any of these values were updated.
6.3.1 Theoretical and Field Considerations

There are three main options for traversal identifiers:

1. A random code (numeric or alphanumeric)
2. An identifier based on the road number or name and further distinguished, as needed, by road type (mainline, spur, ramp, etc.) or political subdivision (e.g., county)
3. A combination of these, where a random code is used for data storage, but a logical road name identifier is available for data entry and reporting.

Two main arguments are often made for use of a random code as a traversal ID. These are:

1. Data Correctness: Not all roads are numbered, and road names may inadvertently be entered incorrectly.
2. Data Change: Road numbers, names, types and political subdivisions are subject to change over time. This would consequently change the traversal ID (and perhaps the links which comprise a traversal).

Any roadway attributes referencing the traversal would need to be updated to use the new ID. For a parts inventory database, this would be analogous to defining part numbers based on each part’s manufacturer, and then having to change a part’s number because the manufacturer changed its name. In database terms, this would be a change to a “foreign key” that would violate the referential integrity of the database. Thus, as standard database design theory indicates, the traversal ID should be independent of the road attributes, including its name, type and political subdivision.

Despite their advantages in computational and database terms, random codes are difficult to use for the end-user. This may be especially for those who record the locations of events in the field or in the office. Therefore, there is a strong practitioner motivation to provide user-friendly and familiar names for traversals, with so-called ‘intelligent’ coding schemes. This is particularly the case where traversals are defined based on roadway numbers or names. The use of road names as external identifiers is further discussed, including institutional issues, in Dueker and Butler (1997).

6.3.2 Real World Implementations

Missouri DOT: The MoDOT Travelways system solves the problem of traversal identifiers by using both random and ‘logical’ traversal IDs. Traversals are defined by named or numbered roadways, with a corresponding logical Travelway identifier consisting of three components:

1. Travelway designation (US, MO, etc.)
2. Travelway name (usually the posted number or name), and

Additional identifiers may include the state name, district number, county name or city name, as needed, to assure uniqueness. For local roads (county roads and city streets), the Travelway name is the full road name. Note that direction is required since separate traversals are defined for each direction of travel (described further in section 6.4). Naming conventions for MoDOT ramps are detailed in section 6.5.2.
products from the state GIS office dropped substantially. As a result, the GIS section could devote more time to applications development, which was also consistent with the desires of the district offices.

All four case studies link their linear referencing methods to their GIS by matching ‘begin’ and ‘end’ measures to the GIS equivalent to the traversal. Events do float between LRS updates to varying degrees, but none of the case study DOTs considered this to be a critical problem. However, the problem of floating events is a well established at some DOTs and is a strong motivator for LRS refinement.

A simplified view of PennDOT’s manual quality control calibration business practice is shown in Figure 49. Field crews collect new DMI linear field measures during a four-year inspection cycle (Block 1). In Block 2, field measures are checked electronically in a batch process and placed into the LRS. These new measures are then extracted into a control load and entered into the GIS quality control cycle (Block 3). The GIS staff sifts through control load paper output looking for inconsistencies between the new LRS measures and GIS network distances as in Block 4. Problems are reconciled and appropriate changes made in Block 5. The ultimate quality control occurs during field use where the data are most familiar (Block 6).

Figure 49 PennDOT’s Manual Calibration Business Process

The following sections review in more detail the coding of LRS in the field. These examples are largely drawn from the case studies.

6.3 Coding Traversal Identifiers

Unique identifiers (IDs) must be assigned to the traversals that can be used for referencing locations in event tables. Section 4.2.3 described traversal organization schemes, the means by which traversals are defined from the underlying links of a transportation network for linear referencing.
3. **Data Collection Direction:** Data may be collected in the non-primary direction of travel, as by a video-logging vehicle, in which case the recorded mileages are not easily converted to the milepoints of the primary direction.

4. **Reference Point off-set:** Recording of some roadway-related data, such as accident locations, is more intuitive when specified as a positive distance from an intersection (or other reference point) in a certain direction, which could be along the traversal in the desired direction (although this would not work for offsets in the wrong direction down a one-way street).

5. **End user Requirements:** End users may wish to have data reported with milepoints increasing in the non-primary direction.

Of these problems, all but the first have typically found solutions that generally meet end-user needs. These have usually been achieved through database coding techniques and conversion routines.

### 6.4.1.2 Dual Direction:

Having different traversals for each direction of travel presents itself as one opportunity to address concerns that exist with just one direction.

The problem of having different lengths for opposing directions has the greatest impact on transportation data management, especially for data that are distance-sensitive such as that found in pavement management systems. Consideration shows that there are potential problems associated with using traversals for both travel directions:

1. **Data entry:** Data entry may be more complicated for direction-specific events, for which travel direction may not have been coded in the past.

2. **Milepoint Location:** Determination of milepoints is more complicated in that each location on a dual-direction roadway has two milepoints, one for each direction of travel. A printed listing of milepoints might have to include milepoints for both travel directions.

3. **Milepoint Direction Distance:** Analysis of roadway data is more difficult where data for both directions is involved, since the correspondence between locations (milepoints) must be established for opposing travel directions.

4. **Directional Conversion:** When reporting information along a roadway, it may be preferable to list all roadway events in a single listing by ascending milepoints in the primary travel direction, which would require conversion of non-primary direction events to the primary direction milepoints.

5. **Distance Calculation:** Rules must be established to assure that roadway miles are not inadvertently double counted. For example, a truck run of ramp might be counted in one direction but not another.

6. **Temporal Changes in Direction:** Rules must be established for reverse-direction lanes, for which the direction of travel changes at different times of day.

7. **Cross-direction Conversion:** To aid data entry and access, automated routines may be needed to convert between milepoints in opposing directions, and to transfer selected data from one travel direction to the other.

8. **Database Queries:** While data query and access applications can be programmed to account for the nuances of dual-direction roadways, ad hoc query of a transportation database would be considerably more complicated for end-users.
6.3.4 Design Implications

The above examples would appear to indicate that any of the methods can be made to work – that is, while referential integrity is a concern, use of road names and other easy to recognize identifiers has also been made to work. This topic should be of some further time and motion research to analyze the tradeoff between:

1. Ease of use: The personnel difficulty of using randomly generated identifiers, and
2. Update: The cost of updating traversal identifiers when random numbers are not employed.

6.4 Use of Separate Traversals for each Travel Direction

6.4.1 Theoretical and Field Considerations

This section briefly reviews field issues for single and dual directions roadways.

6.4.1.1 Single Direction

The use of separate traversals for opposing travel directions, for both divided and undivided roadways, is a major consideration for design of a linear LRS. Traditionally, in most DOTs, each named or numbered roadway is considered a single facility. Thus a single traversal is used for the ‘primary’ direction of travel. The primary direction has to be defined by convention (often “eastbound” and “northbound”). With this traditional approach, the number of traversals would depend on the scheme selected for traversal organization scheme (e.g., bus routes, highway maintenance routes, etc). The direction could be oriented as follows:

1. Route-milepoint method: A single traversal might represent the entire route, eastbound or westbound, or there might be a separate traversal within each county, each oriented in the primary direction of travel.
2. Control section method: There would typically be a single traversal for each control section oriented in the primary direction of travel for the associated roadway.
3. Link node method: It is less likely that the orientation of each link corresponds to a primary direction of travel.

Field inspection and desktop analysis shows that several problems are potentially associated with using a single traversal for both directions of travel. These include:

1. Differing Travel Lengths: The opposite directions of travel may have different lengths, especially for partially or fully divided roadways (including one-way pairs).
2. Direction Associated: Some roadway attributes and events are associated with a single direction of travel, such as “right shoulder width”, HOV lanes and the locations of crashes and signs. Although travel direction can be coded as an attribute, tying such events directly to a direction-specific Travelway simplifies their retrieval.
Table 30  WSDOT Roadway Type Codes

<table>
<thead>
<tr>
<th>Code</th>
<th>Mainline</th>
<th>Code</th>
<th>Mainline</th>
</tr>
</thead>
<tbody>
<tr>
<td>AR</td>
<td>Alternate Route</td>
<td>P1 – P9</td>
<td>Off ramp, increasing direction</td>
</tr>
<tr>
<td>CI</td>
<td>Collector-Distributor increasing</td>
<td>Q1 – Q9 On</td>
<td>Ramp, increasing direction</td>
</tr>
<tr>
<td>CD</td>
<td>Collector-Distributor decreasing</td>
<td>R1 – R9</td>
<td>Off ramp, decreasing direction</td>
</tr>
<tr>
<td>CO</td>
<td>Couplet</td>
<td>S1 – S9</td>
<td>On Ramp, decreasing direction</td>
</tr>
<tr>
<td>FD</td>
<td>Frontage Road decreasing</td>
<td>RL</td>
<td>Reversible Lane</td>
</tr>
<tr>
<td>FI</td>
<td>Frontage Road increasing</td>
<td>SP</td>
<td>Spur</td>
</tr>
<tr>
<td>FS</td>
<td>Ferry Ship</td>
<td>TB</td>
<td>Transitional Turnback</td>
</tr>
<tr>
<td>FT</td>
<td>Ferry Terminal</td>
<td>TR</td>
<td>Temporary Route</td>
</tr>
<tr>
<td>LX</td>
<td>Crossroad within interchange</td>
<td>UC</td>
<td>Under Construction</td>
</tr>
<tr>
<td>PR</td>
<td>Proposed Route</td>
<td>YC</td>
<td>Wye-Connection</td>
</tr>
</tbody>
</table>

The above table also provides a useful classification of highway feature types.

6.3.3  Other Use of Identifiers:

In an ‘A-node B-node’ link-node system, links are typically named based on the node identifiers. For example, the Maine DOT “TINIS” system uses 4-digit codes for nodes, and then names links by concatenating the low-node and high-node numbers. Likewise, link directions are always from low-node to high-node. This creates a problem when two links connect the same two nodes, in which case they would have the same identifier. To avoid non-unique link IDs, a dummy node must be added along one of the two links (see Figure 50). It is best to avoid the fragmentation of the network by such dummy nodes and the associated complications to data collection and coding.

Figure 50  Dummy Node in an A-node B-node Link-node Scheme

Such numbering schemes are used in networks used for many transportation model (that is, model networks used as a basis for replicating current year transportation flows and estimating future years).
9. **LRS and GIS Data Correspondence:** Greater effort is required to maintain the linear LRS and the corresponding GIS data layer.

10. **Database Size Doubled:** The linear referencing control tables and the corresponding GIS data will require nearly twice the number of traversals, which may impede data access performance (particularly for data display in the GIS).

11. **LRM Conversion:** Conversion to other location referencing methods is more complicated.

12. **Business Practice Concerns:** Migration from single-direction to dual-direction traversals usual requires significant changes to business practices, development of support tools and user training.

Given the complications of implementing dual-direction traversals, a common practical solution is to implement separate traversals for all divided highways, and for the divided portions of otherwise undivided roadways. As an option, separate traversals may be defined only for the divided portions of roadways where the difference in length between the two travel directions exceeds some tolerance.

With regard to the NHCRP data model for linear LRS, Vonderohe et al. (1997) discusses issues of modeling bi-directional and multi-lane facilities, including the representation of such facilities by anchor sections and anchor points.

### 6.4.2 Real World Implementations:

**Missouri DOT:** The Travelways system includes separate traversals (“Travelways”) for each direction of travel. The milepoints for each direction increment in the direction of travel, and may have different lengths. Southbound and eastbound directions are designated as primary, and are used to record all data that are not direction-specific. Data access and entry procedures are aided by routines to automatically provide the corresponding milepoint in the opposing travel direction (interpolating between intersections where the lengths differ). Although the MoDOT Transportation Management System (TMS) is not yet in use, end users were generally looking forward to the additional functionality to be provided of dual-direction traversals, knowing that many data entry and management concerns would be addressed by the functionality of the integrated TMS.

In the field, MoDOT uses ‘log books’ listing the milepoints of roadway features that are used to help determine event locations. The design of the logbook for the new LRS has not yet been finally determined. The new logbooks may be more complicated than the previous single-direction logbooks for end users that will now need to reference locations along non-primary directions. However, this complication is offset by new functionality in the Travelways system that will enable specification of location as an offset from a known reference point.

**Washington State DOT:** The TRIPS system distinguishes between ‘increasing’ and ‘decreasing’ traversals for certain types of roadways (see earlier in Table 30). On these roadways, events can be referenced to the desired side of the road. The milepoints in the decreasing direction are the same as for the increasing direction, thus each point on a roadway has a single milepoint. In the GIS, a separate set of traversals (i.e., an “Arc/Info GIS route system”) exists for the decreasing direction traversals.

---

5. Believed to be now going ahead.
Idaho Transportation Department: The MACS/ROSE system defines traversals only in the primary direction of travel, including for divided highways. However, there are cases where the separate directions have very different lengths, in which case different traversals (‘Segments’) have been created.

Pennsylvania DOT: In the PennDOT LRS, there is a traversal for each control section (‘Segment’). Separate traversals (“Segments”) are defined for opposing travel directions on divided highways and for one-way pairs (called, “couplets”). Each segment has its own length and associated offsets, although all offsets increment in the direction of mainline travel. Undivided roadways are represented by single-direction traversals.

6.4.3 Design Implications

Flexibility is required to allow agencies to code traversals in a variety of manner of use. However, the current logic and database issues suggest that using single traversals may be justified. More research is required to exactly pinpoint:

1. Justified circumstances for using dual directions
2. Optimal coding and use practices for using and maintaining dual directions databases.

6.5 Traversal Cases

In this section, a number of “special cases” for defining traversals are addressed. Most of these relate to:

1. The topological intricacies of the roadway network, and
2. The growing need among transportation agencies for more detailed information about the transportation network.

While these cases may be considered in some sense “special” (that is, over the very simplest representation of the network), in reality the forms described here are quite common. Other variations of networks forms (including on those basic forms described here may be considered more truly “special”).

For each special case, options for linear LRS implementation, the relationship to underlying GIS network centerlines, and the strengths and weaknesses of various options are discussed. The special cases considered are:

1. Divided highways
2. Ramps and approaches
3. Non-contiguous traversals
4. Overlapping traversals, etc.
5. One-way pairs
6. Layered or tiered roadways
7. Service roads
8. Individual lanes (including HOV lanes)
9. Associated facilities (e.g., truck runoffs, etc)
10. Rotaries
11. Cul-de-sacs

6.5.1 Divided highways

A “divided highway” is “a highway with separated roadbeds for traffic in opposing directions” (Caltrans, 2000).

6.5.1.1 Theoretical and Field Considerations

Different transportation agencies use different exact in-the-field definitions for a ‘divided’ highway. For example, a highway may be called “divided” if it has:

1. Median Barrier: Divided highways are often defined as having a median barrier, perhaps exceeding a certain width and/or length along the roadway (short medians at intersections may be excluded). For example, in some states, a highway maybe defined as “divided” with a “New Jersey” barrier running down the center (in whole or part).

2. Median Width: A median greater than so many feet

3. Access Control: The level of access control may also be taken into consideration for defining divided roadways. Is fully “grade separated”.

Various methods are used to represent divided highways through linear referencing. The methods used for representing divided roadways are often related to:

1. The format of logical identifiers for traversal, and
2. The use of separate traversals for bi-directional facilities (see Chapter/sections 6.3 and 6.4).

For divided (and undivided) roadways, a principal ‘mainline’ direction is typically defined (for example, in the eastbound or northbound directions of travel). In the case of roadways with bi-directional traversals, this mainline direction is used for coding data that is not direction specific. If a single traversal is used for divided highways, the mainline direction is generally used for the determination of milepoints; in this case, any difference in length for the non-mainline direction of travel is ignored.

6.5.1.2 Real World Implementations:

**Pennsylvania DOT:** A highway is considered to be divided when a median is present, or when there are three or more lanes with at least a painted divider. One segment is assigned to each direction of travel, but offset always increment in the “mainline” direction. Further, all segments will belong to the same State Route.

**Idaho Transportation Department:** The MACS/ROSE system generally does not include separate traversals for divided highways. In some cases where the non-mainline direction is of a substantially different length, a separate traversal (‘Segment’) has been defined, but this is not systematic. Some end users indicated a desire for more accurate length information by use of separate Segments for divided highways.
**Washington State DOT:** WSDOT has no set definition for a divided highway. Separate traversals are defined for each direction of travel, for many undivided as well as divided roadways.

**Missouri DOT:** “Divided” highways have opposing lanes of traffic physically divided by a 4-foot or greater flush median or some form of barrier defined by the AASHTO manual. In the Travelways system, separate traversals are defined for all bi-directional roadways.

### 6.5.1.3 Design Implications

At a minimum, a linear LRS should include definition of separate traversals for divided highways, one-way pairs or other facilities where the length differs above a suitable tolerance for the different travel directions. Consideration is typically given to creating separate traversals at least for fully controlled or limited access highways.

### 6.5.2 Ramps and approaches

A ramp is a connecting roadway between a freeway or expressway and another highway, road, or roadside area.

#### 6.5.2.1 Theoretical and Field Considerations

Highway ramps present a location reference problem because they represent a transition. This can be between for example two routes or a route and another highway segment of highway facility. The ramp without a distinct field coding exercise may not unambiguously a part of either of highway entity. Where ramps are included in a linear LRS, they are typically defined as separate, independent traversals. They are usually associated with one or both of the connected routes either through the ramp naming convention or by their attributes. A standard is usually set for unambiguously locating the begin and end points of a ramp.

#### 6.5.2.2 Real World Implementations:

**Idaho Transportation Department:** Where a ramp merges with an acceleration/deceleration lane, the end of the painted dashed line is used as the end point for the ramp. Although these locations may change when the gore is repainted, this has not been reported as a problem given the type and accuracy of data collected. Also, ramps are related by an attribute to one of the connected highways (typically, the highway with the highest functional class, or lower number within the same class).

**Missouri DOT:** Ramps are named based on the roadways they connect (e.g., `Ramp 54W to 63N N`). Some roadways that appear to be ‘ramps’ in complex interchanges may actually carry the ‘mainline’ route (Travelway) through the interchange. For example, in Figure 51, US 63 N overlaps US 54 W and ‘splits off’ at the associated ramp. Therefore, the Travelway ‘RP US 54 W TO US 63 N N’ is built along this link, but the link also carries the route for mainline US 63 N (the primary Travelway).
Pennsylvania DOT: Ramps begin at the gore point in the PennDOT Roadway Management System. Acceleration and deceleration lanes are treated as an additional lane count within the State Route attribute table. However, field maintenance crews maintain the ramp area including the acceleration and deceleration lanes. Consequently, time and material allocation to ramp-related projects are somewhat perturbed, being allocated in part to a separate ramp Segment, and in part to separate lanes of another Segment. Both management and field personnel see this as a system problem, but the physical database cannot accommodate true field practice.

Washington State DOT: The Related Roadway Type discriminator (part of the traversal identifier) indicates an ‘on ramp’ or ‘off ramp’, and increasing or decreasing direction.

A summary of ramps is given in Table 31.

6.5.2.3 Design Implications

It would appear from these case studies that in short any of the described or reviewed ramp coding methods can work. However, states seem to have implemented many different systems. It would appear that advantageous if one standardized method, at least, from the practical perspectives of

1. Vendors supplying tools on a uniform basis, when they understand what that industry-required basis is.
2. National compilation and more ready comparison of statistics

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Table 31 Implementation of Ramps by the Case Study DOTs

<table>
<thead>
<tr>
<th></th>
<th>ITD</th>
<th>MoDOT</th>
<th>PennDOT</th>
<th>WSDOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ramp traversal definition</td>
<td>Separate traversal for each ramp</td>
<td>Separate traversal for each ramp, for each direction of travel</td>
<td>Separate traversal (‘9000’ series Segments)</td>
<td>Separate traversal</td>
</tr>
<tr>
<td>Ramp end points</td>
<td>At painted gore point</td>
<td>The physical, permanent gore (edge of pavement), if discernible, otherwise the painted gore</td>
<td>Physical gore point</td>
<td>Point of taper</td>
</tr>
<tr>
<td>Acceleration/deceleration lanes</td>
<td>Part of ramp, to end of painted line</td>
<td>Not part of a ramp, lanes are another Travelway attribute</td>
<td>Part of the roadway, not the ramp</td>
<td>Part of the ramp</td>
</tr>
<tr>
<td>Implemented in GIS?</td>
<td>No</td>
<td>Yes</td>
<td>Only for ramps included in the GIS data</td>
<td>Yes</td>
</tr>
</tbody>
</table>

6.5.3 Non-Contiguous Traversals

Traversals are not necessarily contiguous throughout their length.

6.5.3.1 Theoretical and Field Considerations

There are several cases where this may occur depending on how traversals are defined. In cases where named routes, some transportation agencies have chosen to have a single traversal on the overlapping section. In the example in Figure 52, the traversal for Route 5 has a gap where it is overlapped by Route 27. A problem exists in this situation if the milepoints along Route 5 are continuous, in which case the two intersection nodes as pictured would have the same milepoint for Route 5. This situation should certainly be avoided, since a given traversal and milepoint should have a unique location. A preferable system is to have continuous traversals that overlap (described further in the next section).

Figure 52 Gaps in Traversals for Overlapping Routes
Gaps in traversals may also occur if traversals are identified by county (or other political division), and a highway leaves and re-enters a county (see Figure 53). If a single traversal is used within the county, as pictured, and the route has continuous milepoints, then the same problem occurs as for the previous example (the two nodes along the county boundary would have the same milepoint). This situation should be avoided by one of several methods:

1. Use continuous traversals which are not distinguished by county (preferable, where practical)
2. Use continuous milepoints which are not reset at county boundaries, even though the traversals are defined by county
3. Assign separate traversal names to discontinuous sections within each county (e.g., by a numeric discriminator).

**Figure 53 Gap In Traversal That Exits and Re-enters a County**

In the field, it is argued that traversals should not be defined based on political divisions (or on any other attribute of the roadway), but this becomes a practical consideration which often depends on how the data are maintained, particularly when transportation maintenance districts are responsible for recording or performing updates. The issue of non-contiguous traversals is generally not a concern for control section or link-node traversal schemes.

### 6.5.3.2 Real World Implementations

MoDOT and WSDOT use continuous traversals corresponding to numbered or named roadways and which are not distinguished by county or other political division, thus they do not have non-contiguous traversals. (MoDOT currently supports a county-based route-milepoint system for compatibility with legacy practices, but the milepoints are continuous so that locations are not ambiguous). PennDOT and ITD use control sections that are always contiguous.
Regarding the capabilities of GIS, the robustness with which non-contiguous traversals are handled at present differs between the vendors' dynamic segmentation products. Over the long term, this should cease to be an issue as these packages handle such routes more intelligently.

6.5.3.3 Design Recommendation

A LRS should provide for non-contiguous traversals as occur relatively frequently in the field.

6.5.4 Overlapping Traversals

As described in the previous section, traversals may overlap one another. This is typically the case when they are defined based on numbered routes (see Figure 54).

Figure 54 Overlapping Traversals

6.5.4.1 Theoretical and Field Considerations

When overlapping traversals within a single linear referencing method, the location of a point on the overlapping segment may be ambiguous: which traversal is it on? Although either traversal could be used, it is much preferable for purposes of analysis and reporting to have a single method of specifying the location of any point on the network. To resolve this situation, one traversal is designated as 'primary', to which all event data are referenced for the overlapping section. The primary and alternate route designations may be indicated either on straight-line diagrams, or in ‘log’ listings for each route.

6.5.4.2 Real World Implementations

The rules for designating the primary traversal vary between agencies. MoDOT designates the primary route by the Travelway designation (Interstate, US, etc.), then by lowest number (or letter) within each Travelway designation (undivided roadways support two traversals, one for each direction, but these are not considered to be overlapping). In Idaho, control sections are non-overlapping (for any given date).

The MACS/ROSE system also maintains control files for the milepoints along numbered highways and these support overlapping routes for which the measures increase for both primary and alternate routes over common sections. In PennDOT it is general practice for control sections to begin and end at the points where overlaps occur, which ensures a unique ‘address’ at each end.
point. WSDOT selects a primary route by functional class, to which all event data are referenced for overlapping sections.

As mentioned, designation of a primary traversal (and a unique measure for each point on the network) is important for data analysis and reporting purposes. However, it may be very useful to enable data entry by alternate (non-primary) traversals. For example, in the Missouri DOT Transportation Management System, data loaded from another system may include event data specified along an alternate route, in which case it is automatically re-referenced to the primary route in TMS. In this way, data can be collected by familiar means based on routes as signed in the field, but the application assures data are stored by primary traversal.

In the case of PennDOT, cumulative route offsets (for numbered highways) are not continuous across overlapping sections so that an alternate will have the same offset at both the beginning and end points of the overlap. If PennDOT were to enable data input by cumulative route offsets, rules would have to be established to assure that point events were not referenced to ambiguous offset locations.

6.5.4.3 Design Recommendation

Support of alternate traversals on overlapping sections can be useful for data reporting as well as for data entry. It can be useful to enable query of roadway events by any user-selected traversal (or 'route') such that the results are reported along the selected traversal, whether or not it is the primary traversal. For example, if "snow plow" routes were defined as alternate traversals, then it would be useful to print a listing of roadway features and conditions in milepoint sequence along a snow plow route, extracting data that is referenced internally to the primary traversals. This functionality is being implemented in the Maine DOT TIDE system (currently under development).

Some systems have been developed which support alternate, overlapping traversals (or routes), but only a limited number. It is preferable that an unlimited number of alternate traversals be supported, so that additional traversals can be defined as needed for special purposes.

Provision should be made for overlapping traversals, as occur relatively frequently in the field.

6.5.5 One-way Pairs

A one-way pair (or, "couplet") occurs when an undivided roadway temporarily splits into two one-way sections.

6.5.5.1 Theoretical and Field Considerations

This presents a complication to linear referencing when a single traversal is used to represent the undivided highway and a method is needed to separately represent both one-way sections. A common solution is to use a single traversal in the mainline direction of travel, and to define a separate traversal for the one-way portion (or portions) in the opposing travel direction.
6.5.5.2 Real World Implementations

MoDOT support separate traversals for both directions of travel on undivided roadways, thus each leg of a one-way pair is its own traversal with milepoints increasing in the direction of travel. WSDOT defines a separate traversal for the one-way section, using a separate ‘couplet’ roadway type as part of the traversal identifier. In Idaho, if the one-way leg is over 0.01 miles a separate Segment (and hence traversal) is created. For PennDOT, an additional control section (Segment) is created for the separate one-way section, with milepoints increasing in the mainline direction (as for divided highways).

6.5.5.3 Design Recommendation

Provide for one-way pairs, as occur relatively frequently in the field.

6.5.6 Layered or Tiered Roadways

When two roadways are layered or tiered, one on top of the other, they can be handled like any other roadways within a given linear referencing method.

6.5.6.1 Theoretical and Field Considerations

If the two roadways are for opposite travel directions, as on some bridges, then they can be handled like any other divided highway. However, when the linear referencing is to be implemented in GIS, this poses a ‘network pathology’ (Sutton and Bespalko, 1995), where the network features are difficult to represent or display in a GIS. The tiered roadways may be presented by a single line in the GIS, in which case both traversals would be carried on the same line. This could pose a problem, however, if both traversals happened to be primary. In any case, techniques are needed to provide unambiguous data display and graphical query in the GIS environment.

6.5.6.2 Real World Implementations

None of the case studies included specific examples of layered or tiered roadways. All would define separate traversals for each roadway.

6.5.6.3 Design Recommendation

A LRS needs to provide for these as obviously in certain states (e.g., California, Massachusetts Central Artery), a key issue.

6.5.7 Service roads

Service roads parallel one or both sides of a limited access highway and provide a buffer between the limited access and local roadways.

6.5.7.1 Theoretical and Field Considerations

As separate structures, these would typically be designated as separate traversals.
6.5.7.2 **Real World Implementations**

ITD, MoDOT and WSDOT define a separate traversal for each service road. PennDOT would only include the service road if it were a State Route.

6.5.7.3 **Design Recommendation**

The LRS should allow for the inclusion of service roads.

6.5.8 **Individual lanes (including HOV lanes)**

Lane-specific information is sometimes required for some applications.

6.5.8.1 **Theoretical and Field Considerations**

It is typically stored as attributes of the roadway, rather than defining separate traversals for individual lanes.

This is adequate for most purposes, but may present a problem when high-occupancy vehicle (HOV) lanes are considered. HOV lanes are typically separated from other lanes by a barrier, and are often represented separately in transportation models. There are some advantages to maintaining a correspondence between the traversals in a linear LRS and the network elements of a transportation model, particularly for simplifying data exchange between the two.

6.5.8.2 **Real World Implementations**

For all of the case studies, separate traversals were not defined for HOV lanes.

6.5.8.3 **Design Recommendation**

The LRS should allow for the inclusion of individual lanes.

6.5.9 **Associated facilities (truck runoff ramps, rest areas, etc.)**

Associated facilities include rest areas, “points of entry”, truck runoff ramps, etc.

6.5.9.1 **Theoretical and Field Considerations**

For example, an accident in a rest area would be located within the rest area, rather than on the mainline route at a point corresponding to the rest area. To provide this functionality in a linear referencing method, separate traversals would need to be defined within each such facility.

6.5.9.2 **Real World Implementations**

At ITD, rest areas and points of entry (from Canada) are separately mapped at a high level of detail (for end-users), with Segments assigned for each section of roadway within each facility. PennDOT defines Segments for these special use structures (with a special ‘9000 series’ State Route number). MoDOT will not include such facilities in Phase I of the Travelways system, but the linear referencing methods would be easily extended to account for these (with additional
naming conventions). WSDOT locates such facilities as features along roadways, but does not define separate traversals within each facility.

6.5.9.3 Design Recommendation

Ideally, an LRS should enable location referencing within all facilities associated with the transportation network.

6.5.10 Rotaries

These are otherwise called “traffic circles”. They are used more frequently in some states (e.g., New Jersey, Massachusetts) because of their greater theoretical capacity under varying traffic loads. Other states disdain their use because of perceived safety concern from drivers who are not familiar with them.

6.5.10.1 Theoretical and Field Considerations

The representation of a rotary within a linear LRS depends on the desired level of detail. In the past rotaries have often been represented as a point intersection, but this does not necessarily provide the desired level of detail (e.g., for a sign inventory or for maintenance work). Furthermore, this may not correspond to the detail of the GIS data. For example, consider a rotary for two intersecting highways and their corresponding traversals (Figure 55). In this case, a link of the rotary has no corresponding traversal, thus there is no way to specify locations along this link.

Where full representation of the rotary is desired, a suitable approach would be to define a separate traversal for the rotary circle, which would be the primary traversal overlapping any other roadway traversals on the rotary.

Figure 55 Rotary with Link not Accounted for

6.5.10.2 Real World Implementations

In Idaho, in the one case where a temporary rotary was established, a single control section ‘Segment’ was established for the entire circle of the rotary. At MoDOT, the rotary circle could be a separate Travelway, with overlapping Travelways for each incoming roadway (the situation has not yet occurred). PennDOT handles a rotary like other intersections, with no separate control section for the rotary circle. At WSDOT, the situation has not occurred.
6.5.10.3 Design Recommendation

The LRS should allow for the provision of rotaries.

6.5.11 Cul-de-sacs

It is defined as “a local street open at one end only, with special provisions for turning around”. It is distinct from a “Dead End Street” which is defined as, “a local street open at one end only, without special provisions of turning around”.

6.5.11.1 Theoretical and Field Considerations

Cul-de-sacs, as rotaries, become more of an issue as one deals with local roads.

The representation of cul-de-sacs becomes an issue primarily where local roads are concerned. A cul-de-sac may be fully represented or simplified as a point, often depending on the size of the cul-de-sac and the method used to inventory the roadway. In cases where local roads are added to an existing system, the presence of a cul-de-sac may depend on the resolution of the GIS data used as a data source.

6.5.11.2 Real World Implementations

In Idaho, Segments for cul-de-sacs may end in the middle of the cul-de-sac, or may follow the flow of traffic around it. For PennDOT none exist in the State Route system, and for WSDOT these have not been addressed.

In MoDOT, traversals are established for both directions of travel around a cul-de-sac. The southbound or eastbound direction of the cul-de-sac ‘stem’ is considered the primary travel direction, thus counterclockwise around the cul-de-sac is primary. For local roads, the inclusion of cul-de-sacs initially depends on the accuracy of the GIS base map, which in turn depends on the accuracy of the TIGER line work that was merged with the road network coverage by conflation.

6.5.11.3 Design Recommendation

The LRS should allow for the provision of cul-de-sacs.

6.5.12 Proposed roadways

“Proposed roadways” are those in planning and design stages.

6.5.12.1 Theoretical and Field Considerations

The process from concept to design to implementation of a highway can take 25 years or more in some cases. The highway authority may wish to create and manage data for these facilities before they come formally officially into use. They are often inventoried and may be included as official mileage for budget purposes.
Therefore, they are typically included in roadway inventory databases and are assigned traversals and associated (approximate) milepoints. Regarding implementation in GIS, proposed roads may be included in a single road network coverage, or they may be managed in a separate coverage for convenience (as most users do not want to see proposed roads).

Proposed roadways are an example of a *spatial temporal issue*.

6.5.12.2  *Real World Implementations*

For all of the case studies, traversals may be defined for proposed roadways. In the Idaho MACS/ROSE system, a record can be added for a proposed (planned) roadway, with a future effective date. The planned road will not be included in reports until after the effective date. Proposed highways have not been added to the GIS base map. PennDOT enters proposed roads as approximate ('dashed') lines in the GIS, until they appear as permanent features on the USGS quad sheets. At MoDOT, it is undecided at this time if centerlines for proposed roads will be added to the roads layer, or to a separate coverage. A ‘band’ may be added to the coverage for planning corridors.

6.5.12.3  *Design recommendations:*

The LRS should allow for proposed roadways.

6.5.13  *Conclusions on Traversal Special cases*

Overall, as indicated throughout above, provision should be made in a LRS for layered or tiered roadways, service roads, individual lanes, associated facilities, rotaries, cul-de-sacs and proposed roadways.

The following sections consider some measurement, metric and related issues in determining location on with a LRS/network.

6.6  *Use of Mileage Equations*

As previously described, a mileage equation is a formula used to equate two linear measures at the same point along a traversal. They are used in some states when a realignment or re-measurement has occurred.

6.6.1  *Theoretical and Field Considerations*

Historically, one of the major difficulties with linear referencing has been the problem of updating 'downstream' measures when a traversal is updated (i.e., due to a realignment or re-measurement). For example, consider Figure 56 below in which a traversal is realigned (shortened) by 0.1 miles between milepoints 1.0 and 3.0. If the downstream measures (3.0 to 10.0) are all updated (to 2.9 to 9.9), then all references to these traversal milepoints would need to be updated, including any event tables, reference posts or reference points, log books, straight line diagrams and ‘equation signs’ in the field (e.g., as used by ITD). These updates can be a daunting process, especially in the past when manual methods were used.
To avoid these cascading updates, mileage equations have historically been employed so that downstream traversal measures would remain unchanged. In Figure 56 example, a mileage equation of ‘2.9 back = 3.0 ahead’ would be established at the original milepoint 3.0. The obvious shortcoming of this system is that the milepoints are no longer continuous, and the equations must be taken into consideration for any reports or analyses based on the sequential linear measures. Another serious difficulty occurs when a traversal is lengthened, in which case a mileage equation might be ‘3.0 back = 2.9 ahead’, a situation which leads to non-unique linear locations (a common solution is to establishing a separate traversals for the lower and upper portions, often by a naming discriminator).

6.6.2 Real World Implementations

Both ITD and WSDOT use mileage equations. Notably, their LRSs were created 20 and 50 years ago, respectively. At ITD, where LRS updates are common, both system managers and several end users noted problems with the complexities of mileage equations and expressed a desire to eliminate them in any future system revision. MoDOT’s newly developed enterprise LRS does not use mileage equations. PennDOT does not require mileage equations, and the design of their short control sections (about 2500 feet) was in part to avoid the need for these.

6.6.3 Design Recommendation

Mileage equations served an important purpose in the past, when the task of updating references to traversals was overly complex. However, they are generally avoided today given the automated techniques that are now available. In fact, the Ground Transportation Subcommittee of the Federal Geographic Data Committee has recommended that mileage equations not be used in linear referencing systems (FGDC, 1994).

6.7 Location Accuracy

6.7.1 Field and Theoretical Considerations:

Three key summary points may be summarized from the Goodchild (1989) and others (see Longley, et al, 1999) on spatial accuracy:
1. All spatial data are of limited accuracy
2. We have no adequate means to describe the accuracy of complex spatial objects
3. A measure of uncertainty should be associated with every spatial data object.

In other words all spatial data may be viewed as having some measure of error in them. Whether the data is in “in error” may be defined by some measures of whether the data is within some predefined acceptable bounds of closeness to its real world value within a defined schema. Accuracy and error can be defined for:

1. **Positional or locational error** – the distance along the road is “incorrect”:
2. **Attribute or descriptive error** – the values of attributes assigned.

As Goodchild points out, GIS has use has highlighted concerns in spatial data accuracy that did not so prominently occur in cartography. There are several reasons for this, but one is that cartographers were often accorded “cartographic license” in producing maps. In the transportation case, cartographers might “pull” lines where for example at a particular scale it appears a road and a river run conterminously. While this might be correct at a particular map scale, it would not appear correct to the map user, so the cartographer might “pull” the road to one side of the river.

The use of GIS has given heightened concern to accuracy issues over the last decade by the NCGIA research initiative. “Although GIS is seen as little more than a set of technical tools, we believe that the issues of accuracy which emerge when spatial datasets are subject to high-precision objective processing of GIS are fundamental to geography...” (Goodchild, 1989)

We address here the first type of error, positional. Accuracy in linear referencing can be measured in several ways, particularly in a GIS processing context. Consideration may be given to the accuracy of:

1. ‘Official’ traversal lengths (named routes, control sections or links)
2. ‘Official’ linear measures for reference points or control points
3. Event offsets as measured in the field.

Note that these measures are all concerned with the accuracy of distances measured along traversals. These are all linear accuracies, where a distance or offset is always relative to a known point along a traversal.

With LRS implementation in GIS, the accuracy with which point and linear events are displayed can also become a concern. In GIS, linearly referenced locations are linked to the network lines and displayed in geographic coordinates, generally in 2 dimensions. The geographic accuracy of a feature location is measured relative to its Cartesian (x,y) coordinates. In GIS, linearly referenced data may be displayed along with other types of GIS layers, thus it becomes important that a bridge (located by linear reference) be displayed on a river (a GIS layer), and that an accident location be displayed correctly relative to an intersection.

The distinction between linear (x) and geographic accuracy (x,y) is important and sometimes overlooked. The overall accuracy with which linearly referenced data are displayed in a GIS depends on the:

1. Linear accuracy of the event offsets
2. Accuracy of the linear referencing control (traversal lengths, reference point offsets, etc.)
3. Accuracy with which the GIS traversals have been coded and calibrated, and
4. Geographic accuracy of the GIS network lines.

A GIS base map developed (with thorough quality control) from 1:24,000 scale base maps will have an accuracy of about 40 feet. However, the locations of event data displayed in the GIS may be much less accurate than this depending on the linear accuracy of the data.

Many transportation agencies have standards or guidelines for linear location accuracy. For example, all linear measures might be taken to the nearest 0.01 miles (52 feet), including traversal lengths. It is common for individual feature types to have their own accuracy requirements, and to have different linear accuracy requirements for urban and rural areas.

### 6.7.2 Real World Implementations

**Idaho Transportation Department:** By administrative policy, “all official roadway feature locations are maintained to the nearest 0.01 miles.” If a route is re-measured and found to differ from the old length, a difference of less than 50 feet (0.01 miles) is ignored. Within the accident records system, the linear accuracy of each accident location (specified by Segment/milepoint) is assessed based on the information provided on the accident report, and the estimated “plus or minus” inaccuracy is recorded with the accident record. The accuracy with which features are displayed in GIS is poor at larger scales, but this has not been a problem as most maps are at very small scales.

**Missouri DOT:** Most data are currently recorded to 0.01 miles, while some (e.g., functional class) are recorded to 0.001 miles. Beginning and ending measures are being coded for each GIS link on the state system (mainly from ‘old system’ log books, with measures recorded to the nearest 0.01 miles). Key points (e.g., county boundaries, where overlaps start/stop, where divided facilities begin/end) are being updated to 0.001 miles. Milepoints for local roads are being determined from GIS centerline lengths.

**Pennsylvania DOT:** The linear measurement accuracy for PennDOT is about 40 feet. If a Segment (control section) is re-measured, there is a minimum tolerance below which the official length would not be changed, but in general practice the tolerance is ignored and user experience applied. Because the system is re-calibrated Segment by Segment, making such changes is not considered a problem.

**Washington State DOT:** WSDOT has a linear accuracy tolerance of 0.01 miles (52.8 feet). If a traversal is re-measured and found to differ from the old length by less than 200 feet, the length is not updated.

### 6.7.3 Design Implications and Recommendation

The historical datasets found in the case study sites above indicated fairly crude levels of linear estimation. The appreciation of spatial data accuracy issues has improved over the last 10 years mainly in response to the NCGIA research initiative on this topic. However, the one-dimensional case has not been a focus. New technologies of relevance include:
1. Cheaper and highly accurate data collection methodologies
2. GIS, that in theory has infinite precision

LRS needs to be set up to include:

1. Datasets of varying spatial quality, and
2. Accuracy measures

This topic should be further researched. The research might focus on:

1. The current user requirement of state DOTs, given the advent of modern data collection technologies
2. Cartographic reconciliation issues.

6.8 Linear Referencing for Local Roads

Local roads are of increasing focus for the management of transportation network data. This section briefly considers LRS and local roads.

6.8.1 Field and Theoretical Considerations

Depending on context, ‘local roads’ may include roads that do not fall under the state’s jurisdiction, or they may include roads that do not receive federal aid.

To date, state DOTs have been the main users and maintainers of LRS. Traditionally, the have focused on the state (physically) maintained road system. In some states, this has meant virtually all the Class I roads in the state (e.g., North Carolina, with 100,000 miles of state maintained road) while other states maintain only a small proportion of the total road network (e.g., Connecticut has a 5,500 mile state maintained system). Historically, state DOT’s struggled to ‘data maintain’ their state road network and had little time to consider the off-state operationally maintained network.

That situation began to change in the 1990’s. The incorporation of local roads into existing or new LRSs has become a major concern of some state DOTs and other transportation agencies, including with county agencies, MPO’s, (such as with DVRPC, or the Delaware Valley Regional Planning Commission). Interest in local roads is increasing due to a number of reasons, including:

1. **ISTEA General Mandate:** ISTEA legislation emphasized a general concern with data maintenance and integration issues. In short, there was a need to fulfill a general mandate to “manage the state’s transportation system.”
2. **ISTEA Management Systems:** In particular, the ISTEA mandated Bridge (BMS) and Congestion Management Systems (CMS) required the state to be aware of locations on the off-state maintained network. For example, some state maintained bridges may be on the local road systems (as the local agency does not have the equipment and resources to maintain) and CMS sometimes required that traffic be diverted onto local roads in operational plans prepared.
3. **Safety Analysis:** Recording of crash locations on local road
4. Transit Analysis: Support of public transportation data
5. Local Agency Coordination: Closer integration with local transportation planning organizations
6. Fiscal Recording: Maintaining an inventory of all roads receiving state aid.

First among considerations for incorporating local roads are the development and maintenance costs. Development includes extending the linear referencing method to the local roads, and may include integrating local roads in the GIS network (by conflation) and coding the GIS network for dynamic segmentation. Maintenance considerations include how changes to the local road system will be reported or verified, and perhaps how data will be exchanged with local agencies. Where local roads are incorporated, they often have lower accuracy requirements and are less frequently updated.

Depending on the type of LRS, incorporation of local roads into an existing system can be a substantial undertaking. For example, the addition of local roads to a link-node scheme would require that many existing links be split (where they intersect local roads), creating new links in their place. All event data referenced to the old links would need to be updated to the new links. LRS design should include consideration of the impacts of and procedures for incorporating local or other roads in the future.

Local roads more typically include a greater range of the traversal special cases described in section 6.6.

6.8.2 Real World Implementations

In Missouri DOT, local roads are currently being integrated with the state base map by conflation of the 1995 TIGER data. As new nodes are added, their milepoints are being calibrated. Travelways are being defined on local roads based on their road names. Idaho's LRS currently includes only a few local roads, but it would accommodate local roads without modification. WSDOT and PennDOT do not include any local roads in their LRSs (e.g., PennDOT is incorporating some local roads in its GIS base map, where they are used as a backdrop).

6.8.3 Design Implications and Recommendation

Local roads are of increasing interest. LRS practice and design needs to increasingly accommodate for this. Improved potential for DOT's and local agencies to include local roads data may be provided by:

1. New technology and processing tools, such as Conflation, as used by Missouri
2. The inclusion of the special traversal cases.

6.9 Determining Location and Distance: Field and Office Practices

A key component of a linear LRS is the method used to determine linear locations, either in the field or in the office.
Use of Mileposts and Reference Posts

Field and Theoretical Considerations

Various tools and techniques are typically available to field and office staff to determine and record the locations of features and characteristics along traversals. Indeed, one measure of success for a linear LRS is the ease of data collection. A common finding of the case studies is that end-users want to be able to easily record event locations by familiar means, preferably by common roadway numbers and names as signed in the field.

Physical signs are often used in the field to enable determination of linear locations. Mileposts typically display the actual mileage from the beginning of a traversal (aiding travelers as well as data collectors). Reference posts may display a code for which the corresponding offset can be determined from office records. A realignment that changes a roadway's length may necessitate changing the locations of all 'downstream' mileposts, depending on the business practices of each organization (e.g., milepost locations may be updated only if the change in length exceeds a tolerance). Some agencies have abandoned use of mileposts due to maintenance costs and development of other means for determining locations.

Real World Implementations

Pennsylvania DOT: PennDOT uses reference posts (or 'field information paddles') installed when the system was put into place in 1986. The paddles are routinely adjusted as necessary as the network evolves.

Idaho Transportation Department: Mileposts were set for major highways when the original system was implemented in 1978. The mileposts have not always been maintained in their correct locations. It is understood that the true milepoints differ from those posted in the field. However, the mileposts are useful for determining an approximate location in the 'milepost log', from which the accurate milepoints can be determined (the milepost log listing includes the correct milepoints for mileposts, for example, 'milepost 23.0' might have a milepoint of 22.962. By policy, if a milepost cannot be placed within 50 feet of its true location, it should not be installed.

Missouri DOT: Some mileposts were established long ago (mid-1960s?), mainly on interstates and US routes. These are not used in Phase 1 of the Travelways system, but they may be used as reference markers in the future (with associated accurate milepoints, as for ITD).

Washington State DOT: Mileposts are established along State Routes and are maintained by the central office. They are considered to be accurate.

Design Implications and Recommendation

To date the case studies would appear to indicate that there has been a real use for infield milepoints and markers. Will the improved availability of more accurate low cost GPS devices lessen the need for such physically monumentation? It may be five years before “wearable” computers with reasonably accurate locational capabilities included became truly commonplace. State DOTs maybe well aware of the advances in technology here and may be unlikely to institute any fresh field monumentation schemes without giving careful consideration to the effects of the recent announcements concerning GPS accuracy improvements.
6.9.2 Determination of Traversal/Section Lengths

Lengths can be measured with differing degrees of accuracy, and using different field procedures, start and end point definitions, etc.

6.9.2.1 Field and Theoretical Considerations

There are many reasons associated with equipment and user error that can give different length values. As noted above in section 6.8, there are a number of reasons while all spatial data has inherent uncertainty associated with it. We briefly consider here some aspects of measurement of traversals.

Consider for example a GPS-equipped van moving along for the same highway on two different days or even the same day. It will record different traversal lengths (typically, two or three percent different). This is due to for example:

1. The errors associated with the GPS equipment
2. Variations in the strength of signal by day
3. The process used to reduce the GPS data to road centerline data
4. As well as variations in driver behavior (even though drivers might be told to always use a right hand lane, this may not always occur for various reasons).
5. Other factors

Partly as a result of these considerations, but also the need to have an “institutional” distance for funding and other official purposes, DOT’s will often maintain a “log” distance for highways in their jurisdiction. This may changed typically only on a single annual update distance. For these and other reasons, DOT’s often in fact maintain several distances for one section of highway. Each recording activity may record a set of distance traversals that may be calibrated to the “official distance”.

6.9.2.2 Real World Implementations

WSDOT, PennDOT and ITD all relied primarily on distance measuring instruments (DMIs), such as those mounted on videolog vans, to determine the lengths of traversals or the linear offsets for and control points. Where DMI data were not available, distances could be taken from engineering design plans (although this was not preferred as design plans often differ from the ‘as built’). The MoDOT Travelways system relied initially on mileage records from the legacy system for state system roads, which were generally taken for engineering stationing records. County road mileages have been based on DMI-based inventories, while local road lengths have generally been determined by the centerline lengths deduced in GIS’s.

6.9.2.3 Design Implications and Recommendation

The LRS needs to be able to:

1. Maintain and use different traversal measuring lengths and map these to an official log distance.
2. Use improved positional data when this is available.
6.9.3 Determination of Event Locations

Event locations are the positions for which data are recorded on the network.

6.9.3.1 Field and Theoretical Considerations

In the course of data collection and inventory, field and office personnel use various means for determining event locations. The accuracy with which data is collected is very much affected by the nature and type of circumstances it is collected under. For example, a higher degree of accuracy may be associated with standardized collection of positional data on street furniture and highway markings, compared to say, accident location data.

Field methods used may include:

1. More precise measurement from a known point, for example by using a distance measuring wheel, tape, or other automated distance measuring device (e.g., laser measuring device, GPS, etc).
2. Crude estimation of distance from a known or a fixed point or an approximately known or fixed point (e.g., approximately 100 yards from the intersection of park and Lincoln, two block from McDonalds, etc.).

The case studies below illustrate some of the principal options.

6.9.3.2 Real World Implementations

Pennsylvania DOT: PennDOT is unique among the case studies in their use of Straight Line Diagrams (SLDs) as a means of showing the locations of key roadway features and their associated linear measures. The SLDs depict a great deal of information about roadway features and their locations. A substantial problem for their LRS stems from the user’s interpretation of the actual SLD (particularly for elaborate intersections). The symbology is complex and different interpretations ensue based on user experience. In the field, event locations can be recorded as an offset from a referencing marker ‘paddle’. DMIs are also used for determining offsets along control sections.

Idaho Transportation Department: Segment code maps are used for the state highway system by the maintenance districts. Some roadways have a complex sequence of Segments, due to the many realignments that have occurred over the past 20 years, which results in a very complex milepost log printout. Many users would prefer to be able to reference locations using common highway numbers rather than Segment codes. In the field, staff can record locations by noting the distance to nearby intersections, bridges, mileposts or other reference markers. Segment numbers and milepoints are then determined in the office using the milepost index and log for each state or federal highway.

Missouri DOT: Logbooks list the milepoints of static features (used as reference points) along all routes. Users will be able to record locations as an offset from a ‘static’ feature (the only ‘static feature’ available for Phase I of TMS is intersections). Future releases hope to support using the logs of other static features stored in the database such as bridge ends, signs, etc.). The use of separate Travelways for both directions of travel created additional overhead, in that much data needed to be populated in both directions. To minimize this overhead, a routine was
developed to automatically transfer data from one direction to the other. End users found this method to be very effective.

**Washington State DOT:** Permanent physical points (e.g., a bridge), may be used as reference points for determining the distance of an event such as an accident. The bridge location has a State Route Milepoint (SRMP) and an Accumulated Route Mile (ARM) value, so the accident location can be automatically correlated with SRMP and ARM for that route. In the office, the Highway Route Log has a “feature” field that indicates attributes such as bridges, city limits, intersections, markers, etc., with the associated ARM and SRMP values. Another listing (not in the official highway log) details additional roadway attributes such as storefronts, stream crossings, driveways, hamburger stands, etc., and the associated milepoints of these features.

### 6.9.3.3 Design Implications and Recommendation

LRS design needs to allow for event data with varying degrees of positional accuracy.

### 6.10 Linear LRS Maintenance and Quality Control

#### 6.10.1 Theory and Field Considerations

Maintenance of the linear LRS includes performing any necessary updates to the linear referencing control database and to the GIS data (these may or may not be fully integrated). An overview of various methods used to ensure the quality and integrity of the linear referencing control and GIS databases is described below for the case studies.

#### 6.10.2 Real World Implementations

**Idaho Transportation Department:** Quality assurance and control (QA/QC) is performed for some event tables within the MACS/ROSE LRS (verifying that a linear event table covers the entire network), but no routines exist to check the event tables of other operational systems. When event data are added to the MACS/ROSE system, routines verify that Segment codes are valid. The GIS Section of the Planning Division updates the GIS base map internally. GIS updates are not yet synchronized with updates to the mainframe LRS control tables, and only minimal QA/QC has been performed on the GIS data at this time.

**Missouri DOT:** The Travelways Maintenance Application (specifications completed, but to be developed) will perform updates directly in the GIS (ArcStorm or Arc/Info) and transfer the updates to the appropriate Oracle tables of the Travelways system. This process will assure full synchronization between the GIS and linear referencing control databases.

The MoDOT GIS base map is under development. Quality control does or will include full QA of routes (e.g., start and end points), assuring road names agree during conflation, spot checking, performing “frequencies” to identify invalid codes, etc. Mismatches have been identified between field-measured and GIS lengths, but not systematically. GIS centerline lengths are compared with the county road inventory ‘log mile’ lengths as part of ongoing QA/QC procedures. Discrepancies between the LRS and the GIS base map coding exist, but are currently being resolved in the base map.
**Washington State DOT:** As for the other case studies, internal routines are used to verify LRS integrity, such as that linear events cover the entire network (where applicable), or to verify that all event traversal IDs and milepoints are valid.

A process has been developed for updating the GIS base map where a change in an accumulated route milepost (ARM) value is detected and the new value is inserted as the link attribute; the cartographer must then manually adjust the cartographic representation. The GIS base map in not kept fully synchronized with the LRS - routines have been developed to keep them reasonably synchronized, but there is some temporal disagreement between them. Random, informal “checks” are made of the GIS base map against the published road log, although no formal system for validation has been established.

**Pennsylvania DOT:** An LRS batch process scans all records to ensure mandatory fields are complete and to verify that all event table Segment IDs and milepoints are valid. GIS is further used to verify spatial completeness with selected plots. Maintenance procedures for the GIS data, including synchronization with LRS control tables, were described in section 6.10.3

6.10.3 Design Implications and Recommendations

It would appear that there is a need to further deduce and transcribe best national working practices for data maintenance and quality control. It would appear that current methods in use may only partially reflect best practice database procedures.

The design of LRS at the very least needs to allow for:

1. Quality control
2. Temporal data sets and comparison
3. Meta data

Management of historical data is further discussed in the following chapter (see Chapter 7).

6.11 Multimodal Integration

This section briefly reviews the implications of modeling and managing LRS to reflect the needs of different transportation modes. All of the transportation modes are in some way a distinct transportation information community with their own semantics and business practices.

6.11.1 Importance of Multimodal Aspects

Bus, train and air schedules need to be read and interpreted by all. A central argument made from the outset of this thesis has been that disciplinary and professional viewpoint is critical to one’s perspective and appreciation. Tufte adds to skill training, “eyepower and patience”.

As laid out in Chapter 3, such concerns critically apply to the consideration of one-dimensional space. As reviewed in that earlier chapter, the following are key:
1. The different professional or business analysis areas have different business needs and functions they address.
2. The language and analytical tools one will use are biased by professional training or analysis viewpoint.

Transportation covers many modal needs and groups of activities. Many of these transportation groups have historically not worked in close liaison with each other. There is increasing technical, market and institutional pressure to do so. For example, will my GPS route finder operate in my car, or my web device I am using to order pizza work when I am in Seattle, as well as it will in Miami?

In considering one-dimensional space, a review has thus been needed of the different transportation business analysis areas (modes) that use LRS. The realization that a better understanding of LRS business needs was required was an argument the author and others had made in a number of sessions and was becoming better recognized as the “next step” in the LRS field by the late 1990’s.

6.11.2 Theoretical and Field Considerations:

Different modes may be considered as using different modal networks. The California Transportation Plan (1993) lists the various modal networks that comprise the statewide Intermodal system:

One impediment to transportation planning is the separation of information by different transportation modes. Many modes use LRS:

1. **Highway:** The principal user, for highway data maintenance.
2. **Transit:** Along bus lines.
3. **Rail:** Rail systems across the world have typically used mile-markers for operational and maintenance purposes.
4. **Waterways:**
5. **Air:**
6. **Other modes:**

The extension of a single linear referencing system, across modes of transportation, would enable greater consistency in the management and integration of their associated databases. In particular, integration of these different modes would aid the management and analysis of transit information, which often involves transportation by multiple modes.

Conceptually, extension of linear referencing methods to other transportation networks is quite straightforward. Traversals and any associated linear referencing control elements would be defined as for roadways. Not surprisingly, special rules provisions would be necessary in some cases. For example, travel by air and open water is not constrained to linear features. More practically, traversal identifiers must accommodate other transportation modes. As well, multimodal LRSs would likely include a new entity for ‘intermodal transfer point’, where passengers or goods are able to transfer between modes. However, the essential methods of linear referencing are easily applied to any linear network.

6.11.2.1 Real World Implementations:
The MoDOT Travelways system was designed to accommodate non-roadway modes of travel in the future (only roadways are supported in Phase 1). Linear referencing methods for all four case studies are readily extended for other network features. The WSDOT system would require an extended set of ‘related roadway types’ to accommodate any new modes.

### 6.11.3 MultiModal LRS

The NHCRP did give regard to many issues faced by multimodal transportation. It appeared that the greater attention ultimately focused mostly around temporal issues. Other issues including a more precise enunciation of multimodal needs were definitely touched on (especially by the Transportation Planning work group), but were not addressed in such relative detail.

Given the work carried out in Chapter 3 of this thesis on the importance of issues of different network conceptions and linear languages, further attention could have been given to these issues. Also, because the research meeting was organized that the different activity areas went into their own subject area break out groups, there was relatively little “cross-cultural” or cross transportation information community exchange. Thus, some of the differences (and thus needs) in cross-modal business needs were not identified or teased out as perhaps as well as they might be. This is not a criticism of the workshop per se, because inevitably only so much can be covered in a two-day affair. The requirements expressed below come thus in some larger part from integration with the wider analysis already given in this thesis. Certainly, there was not time to fully surface many of the “richnesses” in network pathology examined in the case study examples in this chapter.

The existing NHCRP model, while generic in many aspects, has a highway, state DOT lineage (as it has been supported by the National Cooperative Highway Research Program). The needs of other modes, including transit, or perspectives (such as of ITS) have been less well considered and integrated. Clearly, the addition of a time component was a major need for the transit communities. However, there are other spatial (“multi-spatial”) characteristics that the wider transportation at large requires. These multispatial characteristics seem to be edged out in favor of the multidimensional ones. Many multimodal multi-spatial characteristics will be multidimensional – for example, the ability to convert a 2D GPS data point to a 1D LRS, or a 3D volumetric representation of a highway, but they need to grounded in a fuller analysis of the mode and its requirements.

The multi-spatial characteristics which prior work in this thesis through the case studies has indicated as important include the following six topics:

1. **Multiple Representations of the Same Object**: The same geographic object may be represented, cartographically and topologically, by multiple means. For example, one may wish to represent a bus route in some circumstances by:
   a. A simplified stick diagram
   b. A detailed cartographic map overlaying an existing street map
   c. Showing route variations
   d. Detailed routings in local vicinities, one-way streets or parallel or divided highways, etc.
2. **Multiple Object Forms:** The same named concept may have multiple instantiations. Peuquot notes that "an important capability for geographical modeling applications is to be able to represent alternate versions of the same reality. The idea of multiple realities over time is called branching...the idea of branching time is of independent but synchronous states" (Peuquot, 1999).

3. For example, reference to Figure 39 The NHCRP 20-27(2) Model, page 174, indicates that “traversals” (i.e., routes) may be made up of a whole number of links. Transit operators have bus routes or runs that begin and end mid link. While “work-arounds” can be found to deal with this issue (i.e., create a new link where a bus route starts) the current formalism of the model does not appear to offer flexibility that different modes may require.

4. **Greater Model Flexibility.** In conjunction with the prior two points, modal analysts need to be able to utilize (and, if necessary, adapt) operational models that reflect their working circumstances. On occasion, this adaptation should be facilitated on the fly. The general concept of “Route” is again selected as a key example. The term “traversals” was used in the NHCRP 20-27(2) model, in part as the term “route” was used in so many different ways by the transportation sub-communities meaning different things. Traversal is defined as “an ordered and directed, but not necessarily connected, set of links” (Vonderohe, 1997). However, the ambiguity that exists with the term “route” reflects the reality of the ways that the transportation community as a whole uses this term (for example, a bus route, a highway maintenance route, a rail route, an air route, etc.).

While it was not done in the NHCRP meeting, it would have been instructive in meeting the needs of the transportation practitioner community to map out more exactly all the ways routes are used and the different topological and cartographic features of these required representations. This would represent research that was application-area driven, rather than, model-driven. An example is given below in Table 32 for transit and highway representations.

**Table 32 Route Definition: Transit and Highway**

<table>
<thead>
<tr>
<th>ROUTE EXAMPLE</th>
<th>Mode</th>
<th>Temporal Aspects</th>
<th>Spatial Aspects</th>
<th>Important Associated Features</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 “Simple”</td>
<td>Highway Maintenance</td>
<td>Usually fixed; occasional updates</td>
<td>Whole links</td>
<td>None critical, many desirable</td>
</tr>
<tr>
<td>2 “Complex”</td>
<td>Transit</td>
<td>Links time variant over day, week, etc:</td>
<td>Links and part links; store spatial variations as one (master) route</td>
<td>Bus stops features of the route</td>
</tr>
</tbody>
</table>

5. **Multimodal Term Mapping:** Multimodal representations need to be “inter-communicatable”. For example, if one is transferring from a bus line to a rail line, there
needs to be a mechanism for determining common points in time and space. One would therefore be able to readily work across mode timetables and schedules that as Tufte has indicated can represent a challenge in one mode.

6. **Multimodal Accuracy Flexibility**: Multimodal applications need to be able to express location in time and space in terms and in accuracies and forms appropriate to the mode. For example, bus location may be expressed relative to:
   
   a. Nearest bus stop  
   b. Street intersection, or  
   c. Time point  

Train location may be expressed for example relative to milepoint or timepoint.

7. **Data Generalization / Ungeneralization**: Modes should be able to keep data at different levels of accuracy and precision appropriate to their needs. There should be tools to:
   
   a. Integrate these data sources, which may be of different spatial sources and quality  
   b. Carry out topological and cartographic merges  
   c. But then, extract the data by mode at the level of cartographic quality in which it was originally prepared.

The above are the top six higher-level functional requirements noted for multimodal LRS.

6.11.4 **Design Implications**:

Clearly, LRS designs that might allow flexibility of moving data across multi-modal contexts would have significant advantage. There is an additional need to include flexibility in modeling different network forms and hierarchies, that may reflect the set-up and use of networks by different modes.

6.12 **Chapter Summary and Conclusion**

6.12.1 **Progress Achieved**

This fairly lengthy chapter has summarized the results of the DOT case studies; however the variations in the network features described has meant that much of the review provided here has been kept at a somewhat summary level. Only treated a limited number of network examples (or “pathologies”) such as cul-de-sacs and dead end streets have been reviewed.

6.12.2 **Ten Key Observations**

Table 33 below gives a brief summary of ten of the main findings recorded in this chapter. The two immediately following tables provide some further break out detail.
<table>
<thead>
<tr>
<th>#</th>
<th>LRS Issues</th>
<th>Key Observations and Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coding traversal identifiers</td>
<td>Any method can work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Road names a reasonable choice</td>
</tr>
<tr>
<td></td>
<td></td>
<td>More research needed</td>
</tr>
<tr>
<td>2</td>
<td>Use of separate traversals for each travel</td>
<td>Field use benefit from dual direction</td>
</tr>
<tr>
<td></td>
<td>direction</td>
<td>Logic and database issues with using</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single traversal at the current time as issues</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with the current technology</td>
</tr>
<tr>
<td>3</td>
<td>Special cases for defining traversals.</td>
<td>SEE Table 34</td>
</tr>
<tr>
<td></td>
<td>These include: a) divided highways, b) ramps,</td>
<td></td>
</tr>
<tr>
<td></td>
<td>and, c) overlapping traversals, etc.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Use of mileage equations</td>
<td>Served an important purpose in the past</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Several DOT's use today</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With new technology, now recommended that do not use</td>
</tr>
<tr>
<td>5</td>
<td>Location accuracy</td>
<td>Spatial data of varying quality</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Need to set up LRS with flexibility to deal</td>
</tr>
<tr>
<td></td>
<td></td>
<td>with datasets of different accuracy and accuracy measures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>More research needed</td>
</tr>
<tr>
<td>6</td>
<td>Linear referencing for local roads</td>
<td>Growing need to include local roads data as</td>
</tr>
<tr>
<td></td>
<td></td>
<td>local agencies manage roads more</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Local roads more detail</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Need to include greater range of traversal types</td>
</tr>
<tr>
<td>7</td>
<td>Determining location and distance: field</td>
<td>SEE Table 35</td>
</tr>
<tr>
<td></td>
<td>and office practices</td>
<td></td>
</tr>
<tr>
<td>8</td>
<td>Linear LRS maintenance and quality control</td>
<td>Need to define best working practices – work here a small start, but more</td>
</tr>
<tr>
<td></td>
<td></td>
<td>needed:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Design of LRS needs to include: a) Quality Control, b) Temporal factors,</td>
</tr>
<tr>
<td></td>
<td></td>
<td>and, c) Metadata</td>
</tr>
<tr>
<td>9</td>
<td>Multimodal Integration</td>
<td>Multimodal real need if use of LRS to be extended</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Additional need to include flexibility in</td>
</tr>
<tr>
<td></td>
<td></td>
<td>modeling different network forms and hierarchies</td>
</tr>
<tr>
<td>10</td>
<td>Temporal issues.</td>
<td>(See Ch 7)</td>
</tr>
</tbody>
</table>
Table 34 Traversal LRS Recommendations

<table>
<thead>
<tr>
<th>#</th>
<th>Traversal Special Cases</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Divided highways</td>
<td>Allow for (including different forms)</td>
</tr>
<tr>
<td>2</td>
<td>Ramps and approaches</td>
<td>Allow for Provide one consistent method</td>
</tr>
<tr>
<td>3</td>
<td>Non-contiguous traversals</td>
<td>Allow for (common issue)</td>
</tr>
<tr>
<td>4</td>
<td>Overlapping traversals, etc.</td>
<td>Allow for (partic. for PT)</td>
</tr>
<tr>
<td>5</td>
<td>One-way pairs</td>
<td>Allow for</td>
</tr>
<tr>
<td>6</td>
<td>Layered or tiered roadways</td>
<td>Allow for (esp states where common)</td>
</tr>
<tr>
<td>7</td>
<td>Service roads</td>
<td>Allow for</td>
</tr>
<tr>
<td>8</td>
<td>Individual lanes (inc. HOV lanes)</td>
<td>Allow for</td>
</tr>
<tr>
<td>9</td>
<td>Associated facilities (e.g., truck runoffs, etc)</td>
<td>Allow for</td>
</tr>
<tr>
<td>10</td>
<td>Rotaries</td>
<td>Allow for</td>
</tr>
<tr>
<td>11</td>
<td>Cul-de-sacs</td>
<td>Allow for</td>
</tr>
<tr>
<td>12</td>
<td>Proposed roadways</td>
<td>Allow For</td>
</tr>
</tbody>
</table>

Table 35 LRS Field Practices Recommendations

<table>
<thead>
<tr>
<th>#</th>
<th>Field Practices</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mileposts and Reference Posts</td>
<td>Useful in short-term In longer-term, GPS negate need for?</td>
</tr>
<tr>
<td>2</td>
<td>Determination of Traversal/Section Lengths</td>
<td>Be able to maintain and use different traversal measuring lengths and map these to an official log distance. Be able to use insert positional data when this is available.</td>
</tr>
<tr>
<td>3</td>
<td>Event Locations</td>
<td>Also, allow for event data with different degrees of accuracy</td>
</tr>
</tbody>
</table>
Different traversal types are summarized in Table 34. It can be seen that the common recommendation throughout is that these different traversal types need to be allowed for. These reflects a practitioner goal of reasonably allowing model forms that meet clear working practices.

The limited set of reviewed other LRS field issues reviewed are summarized in Table 35.

6.12.3 Main Conclusions

A summary of LRS implementation and use for the case study DOTs is shown in Table 36.

Table 36 A Comparison of State DOT Incorporated Technologies

<table>
<thead>
<tr>
<th>ITD</th>
<th>MoDOT</th>
<th>PennDOT</th>
<th>WSDOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>GPS</td>
<td>no applications</td>
<td>incorporated with enterprise LRS</td>
<td>data fields added – vans being equipped</td>
</tr>
<tr>
<td>Data log vans</td>
<td>mission essential</td>
<td>mission essential</td>
<td>mission essential</td>
</tr>
<tr>
<td>Video log</td>
<td>mission essential</td>
<td>under development</td>
<td>under development</td>
</tr>
<tr>
<td>Straight line diagrams</td>
<td>not used</td>
<td>not used</td>
<td>mission essential</td>
</tr>
<tr>
<td>ITS/IVHS</td>
<td>no applications</td>
<td>urban freeway cameras for congestion monitoring</td>
<td>urban freeway cameras for congestion monitoring</td>
</tr>
<tr>
<td>Data warehousing</td>
<td>no applications</td>
<td>extension of enterprise system</td>
<td>no applications</td>
</tr>
<tr>
<td>RDBMS for LRS control</td>
<td>not used</td>
<td>mission essential</td>
<td>not used</td>
</tr>
</tbody>
</table>

It may concluded more generally quite clearly that in short:

1. Coding of LRS is dependent on the underlying network spatial form.
2. There is a variety in the spatial form in real world transportation networks
3. “Field coding” of even simple “in the field” linear referencing cases shows opportunities for use many alternative schema.
4. Use of alternate coding schema can lead to difficulties in operability between these schemas (however well in theory they may well be conceptually integrated)
5. Conceptual Extensions are needed in various areas. These include in particular for:
   i. The variety of network forms found
ii. Multi-modal applications
iii. Temporal applications

The following chapters attempt to provide some consideration of approaches to dealing with these particular issues.
6.13 Chapter References


7 Temporal Considerations of LRS

Time:
Duration; period, term, stage, space, span, spell, season; the whole time, the whole period; space-time; course; snap; epoch; time of day, time of night; hour, minute; very minute &c., very time, very hour; present time, right time, true time, exact correct time. corridors of time, sweep of time, vesta of time, course of time, progress of time, process of time, succession of time, lapse of time, flow of time, flux of time, stream of time, tract of time, current of time, tide of time, march of time, step of time, flight of time...


7.1 Chapter Introduction and Purpose

You can never truly stand in the same river twice. The issue of time has likewise historically posed significant problems for transportation spatial data handling.

As with LRS, the basic concept of time is simple. However, the human actuality of it is more complex. There are many different ways to consider time and temporal referencing methods (e.g., zone standard time, Greenwich Mean Time, watch or clock time, "MIT thesis deadline time", game time, etc.). Time can itself be linear. Or, it can be cyclic, branched, discrete or a combination of these simultaneously.

This chapter expands the analysis of LRS issues by focusing on the addition of modeling time and multimodal aspects relating to LRS. The chapter draws together:

1. A review of research on the temporal aspects of GIS
2. Considerations of the temporal aspects of LRS gained from undertaking the case studies
3. Expert Panel review of temporal aspects related to LRS

The chapter seeks out an initial set of additional related basic functional requirements for time and multimodal LRS.

GIS as a whole is divided into the components of space, time and attribute. GIS time (TGIS) is an acronym which may be confused with GIS-T or because some agencies call it transportation GIS. Compared to space and attribute aspects, it may be argued that the TGIS field relatively has been ignored. Vendors have invested relatively little. Researchers have lacked funding and have had many other areas to focus attention. No fuller, field synthesis or more generally agreed approach has yet been formulated or adopted (though the NCGIA did some review work in the early 1990's, which was recently published as a set of papers – Egenhoffer, et al, 1998). However, because of its importance and the fundamental issues and problems it raises, TGIS may be considered currently an active and cutting edge GIS research area.
The consideration of the modeling of GIS-T time can best be done within the wider context of TGIS and ultimately, in a practitioner sense, in COTS TGIS. Little work has been done specifically in the modeling of time in a transportation spatial or GIS-T context. Any adopted solution will ultimately in a field context likely have to relate to wider field (TGIS) solutions for dealing with temporal issues. It is there important for the GIS-T and LRS communities to be aware of developments in TGIS. However, each application domain needs to take assessment of its own specific research needs and field issues.

Consideration of temporal or multidimensional aspects of GIS are made more complex by their consideration from a variety of viewpoints. These considerations include in short:

1. **Temporal Application Models.** Do we understand how time is conceived, setup and managed? This area includes gaining an understanding of the way time is considered or used in the particular application area. (Several different “types” of time are noted in the quote form Roget’s thesaurus at the beginning of this chapter and are listed below). For example, what time segments or “time slices” are appropriate for the particular application?

2. **Temporal Data Models.** Current in-use databases offer a limited number of off-the-shelf methods of storing temporal data. This may be a strong practical concern from a practitioner viewpoint.

3. **Transportation Data Collection and Storage.** What time segments or “time slices” are appropriate for the data collection part of the application? Castagneri (1998) points out that even time should have metadata associated with it as it may not be set-up and collected within a uniform basis.

4. **Temporal User Interfaces:** This includes the design of interfaces and languages for managing and dealing with spatially related data.

The analysis and summary design requirements provided in this chapter is based on:

1. **Temporal Research Review.** A brief additional review of existing and ongoing research was carried out.
2. **Research and analysis** carried out in the course of this thesis (see Chapters 6 and 7), including, in particular, the state DOT LRS case studies (see especially Section 7.10), as well as a wider LRS literature review.
3. **An NHCRP workshop.** Participation was made in an NHCRP research activity related to this project.

A basic set of high-level requirements gained from the above exercises were listed out and integrated to form a composite list. A summary listing of additional functional LRS requirements as they were deduced on the basis of the work is made.

### 7.2 Transportation Time

*Schedules are among the most widely used information displays, with a sheer volume of printed images comparable to road maps ... The issues of timetable design are at the heart of envisioning data — large arrays of*
Tufte (in quote) rather neatly encapsulates the importance and difficulty of the layout and interpretation of network based data.

Optimized handling of temporal data is fundamental to the business of transportation agencies, for two main sets of reasons. These are:

1. **Historical Analysis**: Through analysis of trends and cumulative effects that investment into the transportation system can be optimized. Justifications for significant expenditure (for example for safety remedial measures or realigned or new highways) are often based on cumulative historical data analysis and trend analysis.

2. **Real-Time Decision Support**: New technologies such as GPS and ITS have made the real-time processing of transportation spatial data a much more critical issue. GPS and remote sensing have made available vast quantities of data that have a much higher currency than previously experienced.

Historical data management is also one of the main challenges and focuses of linear referencing. Location is the key to highway data integration but location references change over time (e.g., due to realignments, re-measurements, renaming of traversals, etc.). Historical data management must key old and new geometry (and attribute data), with values to reconstruct all prior cases. Updates to the LRS may be difficult to convey to separately managed, ‘remote’ operational data sets, due in part to reliance on remote data managers to update their own databases, and on the vertical organization of transportation systems within an agency. Historical data management is often fragmented or incomplete within an LRS and that full access to and analysis of historical data is often limited.

Networks and the activities that occur on them change over time, in various increments. A highway performance database may get an official update once a year; a vehicle or traffic monitoring systems maybe every few seconds. At one extreme, the physical structure of highways change relatively little over time; however, they do change, typically over 3 to 5% of the roads in a state DOT maintained database have some change in geometry or traffic arrangements each year. At another extreme, operations of transit vehicles are vitally concerned with real time, many activities being time dependent. For example, the feeder bus may not leave the station until the train arrives. Different modes of transport create, manage and analyze networks differently.

7.3 **Recent Research in TGIS**

As was noted in Chapter 1, while GIS has been in use for 25 years or more, more complex modeling issues (including the consideration of time in a spatial context) have only relatively
more recently been considered. Commercial information systems do directly address time today. Many GIS texts particularly until more recently barely mention the handling of time.

The analysis of time base data is typically done in the field by taking "time snapshots" and making whole database to whole database comparisons – that is, the ‘deltas of change’ are not stored for a time series but rather a snapshot of the whole spatial and attribute database.

Formal research on time in GIS has recently begun to grow (on which GIS-T or LRS developments could be based). Most of this work reflects mostly review studies or partial test implementations to date. Langran (1992) published the early work in this field. Egenhoffer and Golledge (1998) provide a collected set of edited papers on temporal reasoning in GIS.

More focus here is explicitly made on time because in short:

1. It is a clear need for modal transportation applications
2. It is needed to integrate use of transportation modes
3. There is more existing research and literature.

The earliest spatial temporal research of Langran (1992) has made clear that time can be analyzed in at least three distinct generic ways:

1. *World time:* The actual time an object changes.
2. *Measured Time:* The time the object changes.
3. *Database Time:* The time the change is actually recorded in the database.

Laurini et al (1992) notes that time may be considered and included in a GIS currently in several ways:

1. *As a basis for recording events or attributes.* A map maybe produced at a particular point of time, for example, annually. For example, for the safety management system, a safety map product might be created showing accidents in the month of May. The spatial maps products are created on a set cyclical basis.
2. *As an attribute of an entity with unchanging spatial properties.* Data may consist of the changing dates at which events occurred. A set of data can have a changing number of occurrences of an event. Thus, for example traffic accidents may be recorded at the particular points of time and location as they occur.
3. *As a framework for observing changes in the spatial entities (that may have changing spatial properties).* In this way of time handling, the focus is on the changing object. For example, conceptually, one might desire to store a roadway so that it cartographic and topological features could be stored and generated for a particular point of time.

The *goals* of a TGIS are itemized below, adapted from Langran (1992).

1. *Inventory:* Store a complete description of the study area or network, and account for changes in both the living world and computer storage.
2. *Analysis:* Explain, exploit, or forecast a region's or network components and processes.
3. *Updates:* Supersede outdated information with current information.
4. **Quality:** Control and evaluate whether new data are logically consistent with previous versions and states.

5. **Scheduling:** Identify or anticipate threshold database states, which trigger some sort of action by the system.

6. **Animation:** Display a dynamic summary of regional processes.

7. **Static Mapping:** Display spatio-temporal facts by traditional cartographic means.

A number of data model approaches have been considered for the inclusion of time into GIS. These include:

1. Time-stamped individual layers, such as the “snapshot model”
2. Time-stamped attributes, as in the spatio-time composite model
3. Time-stamped spatial objects, as in the spatio-temporal objects model.

Candy (1995) in his thesis reviews these models and adapts a COTS GIS to support time stamped entities.

NCGIA initiatives have considered the inclusion of time aspects. In particular, NCGIA Research Initiative 10, considered *Spatio-Temporal Reasoning in GIS* (Egenhoffer, 1994). This initiative was largely focused around two workshops one held in Orono in 1990 and one held with European researchers in Italy in 1992. A meeting to prioritize research issues focused on the need for alternatives to the snapshot space-time model, by for example, considering processes. Participants identified a proposed TGIS research agenda consisting of three complementary parts:

1. Studies of human cognitive representation, language, and culture with respect to geographic space and time
2. Developments of formal systems for spatio-temporal reasoning; and
3. Efforts to bridge the gap between human and formal systems with appropriate means for communication and interaction.

This thesis earlier (Chapter 3) gave a little consideration to language issues. It is interesting to note a conclusion of the NCGIA research teams in terms of language and linguistic issues.

*What kinds of models of the world does language yield?* The temporal model that our language provides is very strange. Most languages do not allow you to assign a temporal name to a spatial object. Language gives you wonderful economy in describing space. The ambiguity is often considered a disadvantage, but is it? There is a default meaning that we apply based on context. Language allows ambiguity. Is the ambiguity helpful or is it a negative? Verbal instructions will probably become more important in GIS. "Take the next exit" works better than looking at a map in a Vehicle Navigation System. What element of the instructions are spatial vs. temporal? Language can more precisely capture uncertainty than graphics. What kind of spatial-temporal phenomena are better understood/utilized via language (e.g., driving directions) and what kinds are better understood/utilized via graphics (e.g., maps). (NCGIA 1993)

Sixty more detailed researchable questions were identified. It is not certain by the year 2000 how many if any of the specific research questions identified or wider initiatives have been formally taken up.

Guptil notes that one method to treat time is as an attribute (Guptil, 1995). He uses a road example.
Basic feature: Road segment  
Perm ID: 101  
Composed of: Spatial objects (SO) 1,2,3  
Feature observed: 12 July 1963  
Feature Expired: current

Here the time information is provided just as any other attribute. He further examples a road having two lanes for a period of time then four lanes.

Basic feature: Road segment  
Perm ID: 101  
Composed of: Spatial objects (SO) 1,2,3  
Feature observed: 12 July 1963  
Feature Expired: current

<table>
<thead>
<tr>
<th>Attribute</th>
<th>Number of lanes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Value</td>
<td>2</td>
</tr>
<tr>
<td>Value Observed</td>
<td>12 July, 1963</td>
</tr>
<tr>
<td>Value Expired</td>
<td>3 May, 1976</td>
</tr>
<tr>
<td>Value</td>
<td>4</td>
</tr>
<tr>
<td>Value observed</td>
<td>3 May 1976</td>
</tr>
<tr>
<td>Value Expired</td>
<td>Current</td>
</tr>
</tbody>
</table>

Guptil reviews issues with time-stamping datasets. He uses the case of distributed databases, long transactions and the “two-stage commit” update on a road dataset to example some of the practical field issues than can occur with time-stamping. He shows that a host on uncommitted dependency problems can exist when some error is determined and a transaction remains uncommitted.

Guptil further reviews some of the data quality issues associated with temporal measures, and their association with other attributes. The measures he reviews are a fairly standard set used to review spatial data quality:

1. Lineage  
2. Positional accuracy  
3. Attribute accuracy  
4. Completeness  
5. Logical consistency  
6. Semantic accuracy

Taking up the earlier 1990’s NCGIA call for more process focused or process-driven handling of time, (vis-à-vis temporal extensions to spatial data models) Claramunt and Li (1999) have proposed a constraint solving temporal logic method to deal with spatial applications. Constraint propagation is proposed as an important method in reasoning about time and change. Composite processes have a set of component processes that maintain the temporal properties. They propose a constraint propagation algorithm that they apply to a transportation network problem. Their work would appear to represent a fairly early stage in the formulation of process-driven approaches.
Peuquet (1999) has been a leading reviewer and researcher of the handling of time in geographic databases. He notes that the major reason for modeling time is to denote change and that "change" can be grouped into four generic patterns:

1. **Continuous.** Going on throughout some interval of time.
2. **Majorative.** Going on most of the time.
3. **Sporadic.** Occurring some of the time.
4. **Unique.** Occurring only once.

Peuquot indicates maintaining coherence between aspatial and spatial attributes which are both changing over time is tricky. He notes that a number of researchers in the 1990's have pointed to an object oriented (OO) approach as a possible way forward. The OO approach is seen as appropriate as one of its features, *encapsulation*, in short provides that the components of a particular thing are stored as an integral unit. This would hide much of the complexity from the user. Another feature of OO, *inheritance*, allows for explicit linkage of characteristics from one class of objects to a sub-class. While often pointed to, there has been little work to explore out and to actual provide specification and demonstration of an OO approach. Chapter 10 of this thesis takes some first steps in this direction.

As reviewed, current GIS COTs do not handle time aspects directly. Peuquet notes that "much remains to be done before a true temporal GIS can be realized". He points to the need for interdisciplinary research and the need to develop better understandings of temporal representation issues.

### 7.4 Temporal issues: Management of Historical Data

The issue of time has proved an especially difficult and key one in the field for transportation agencies. The sections below relate observations on TGIS from the thesis case studies.

#### 7.4.1 Synchronization of Linear LRS control and Event Databases

Updates to the linear LRS control database involve several different types of updates, including:

1. Correction to traversal lengths or control point measures (no physical change to the network)
2. Realignments (modified network, often affect 'downstream' traversal measures)
3. Addition of roadways (which may extend existing traversals)
4. Abandonment of roadways (which may impact portions of traversals and their measures)
5. Introduction of a new node along a route (may impact an existing traversal).

Updates may occur even when there has been no physical change to the network (e.g., a correction to milepoints along a route). These updates may take place in the LRS control database, on straight-line diagrams or other paper records. In addition, any updates to the LRS may require corresponding updates to any event tables that reference the updated portions, by rectifying the linear references to agree with the updated LRS control database. Alternatively, event tables may be date stamped so that they will now reference historical records in the control tables.
It is common for event tables that are integrated with LRS control files in a uniform application to be automatically rectified when updates occur to the LRS. In contrast, a problem often exists for 'remote' event tables (e.g., pavement management system, sign inventory, etc.), which are managed completely separately from the LRS control database. For these, it is not uncommon that an update to the LRS control tables is not automatically reflected in the remote database, in which case the event tables will no longer be “synchronized” with the LRS control. In this case, if the event data is linked to the current LRS as coded in a GIS base map, locations may either be displayed in incorrect locations or not displayed at all. Furthermore, any analysis involving historical data would likewise be impacted. Synchronization of LRS control and event databases is therefore a central problem for managing historical linearly referenced data.

7.4.2 Use of Periodic Archives of Historical Data

Various techniques have been applied for managing historical linearly referenced data with different levels of functionality. At the lowest level, users would be able to access archived “snapshots” of data related to the transportation network. This could be accomplished, for example, by saving annual or semi-annual snapshots of event data, along with the synchronized GIS network on which the LRS is implemented. Archived historical data sets enable display and overlay of historical data from different dates on a common map. As well, users can generate summary statistics for different dates, and compare those summary statistics (for example, to compare the percentage of state highways having sufficiency ratings below a given tolerance as of different dates).

However, while periodic snapshots provide basic access to historical data, this system has several limitations. First, a complete copy of the GIS network and related event tables must be stored with each dated version, although much of this data will be redundant (most of the physical network and many of the roadway characteristics are static from year to year). Second, data stored for different dates cannot easily be directly compared, road segment for road segment, since each version of event data is referenced to a different network. Visual comparison is possible by displaying data from different dates on the same map, but even this method is limited by the complexity of symbology needed to display two complete networks and their related attributes (or events). Full comparison of archived data from different dates would require that the two networks be joined by conflation, so that any linear features modified between the two dates could be identified, along with any updated measures for the linear LRS. Finally, any event data sets not stored with the periodic archive could be difficult to synchronize with a specific historical network. For these reasons, periodic archives have quite limited functionality.

7.4.3 Enabling Segment-level Comparison of Historical Data

A higher level of functionality would enable ‘segment-level’ comparative analysis of data from different points in time. With a segment-level comparison, conditions at two different times are compared along arbitrary roadway segments. This would enable queries of the type, “identify highway segments which had condition A at a given date in the past, but which now have condition B.” A query of this sort requires that the system be able to compare each segment of the current network with its corresponding segment on a historical network.

Once highway segments have been classified based on how they have changed over time, they can be mapped using a single symbol to identify the degree of change. For example, maps or reports could be generated which indicate how pavement conditions have changed over the past 5
years for each highway segment (e.g., “better”, “same”, or “worse”). This functionality can be contrasted with the simpler system where past and present conditions are mapped together, and the user must decode the combined symbology to determine how different road sections have changed over time.

Regarding statistical analysis, a segment-level comparison (between different dates) provides much greater flexibility for reporting changes over time than is afforded by the use of archived data sets. Summary statistics generated at different points in time provide results such as, “The portion of the state highway system in ‘poor’ condition has decreased from 15% to 12% over the past 5 years.” Additional detail can be provided by segment-level comparative analysis, such as, “Whereas 5% of state highways in poor condition were improved to acceptable levels, only 2% deteriorated from acceptable levels to poor condition.” A map could then be generated highlighting those highway segments that had deteriorated or been improved.

To enable segment-level comparison, the system must be able to reference event data from different times to common linear measures along the network. Any changes made to the LRS between the dates of the two data sets must be accounted for. In a named route/milepoint system, LRS updates might include a correction to traversal measures, or a change in a traversal identifier due to realignment in the middle of a traversal. In a link/node system, link identifiers may change as new nodes are introduced. For any type of LRS, changes to the underlying linear control elements (routes, links and/or measures) will require some sort of rectification between the event data sets in order to compare past and present conditions at the segment level.

7.4.4 Management of Historical Centerline Alignments in GIS

In order to display historical data referenced to historical traversals, it is necessary to store the historical traversals (and alignments) in the GIS. This can be managed by storing historical traversals in a separate GIS layer, which can be combined with the current network as needed for performing historical analyses. Alternatively, all historical alignments and traversals can be stored in a unified GIS database that is fully synchronized with the linear referencing control database (or fully integrated with it). Due to the relatively recent support of linear referencing in GIS and the typical separation of GIS from other information systems functions, it is more common for the GIS data to be maintained only for the current road network. As the tools for managing linear LRS in GIS become more sophisticated, it is likely that full management of historical alignments in GIS will become more common.

7.4.5 Real World Implementations: Experience From the Case Studies

This section summarizes management of historical data as practiced by the case studies. A comparison of the impact of LRS updates on different linear referencing methods is provided with the general comparison of linear LRM in section 4.2.2.

Idaho Transportation Department: Historical data is managed in ITD’s MACS/ROSE system by a special type of control section uniquely identified by:

1. A Segment ID
2. The begin/end milepoints, and
3. The effective and expiration dates.
The effective and expiration dates serve to keep track of and manage any updates to the LRS over time. Event data stored on-line in the MACS/ROSE system also has effective and expiration dates, so that historical events can be related to the correct control section. A ‘Segment’ may include many of these control sections, and at any given point in time each segment is completely represented by non-overlapping control sections (although historical control sections may overlap).

The definition of a traversal is complicated in the MACS/ROSE system by the way historical data is managed. A traversal may correspond to an entire ‘Segment’, which has unique milepoints at any point in time (although they may not be continuous). Alternatively, the traversal may correspond to a control section distinguished by effective and expiration dates. These ‘control section’ traversals would be required for display of historical data, whereas full ‘Segment’ traversals would be adequate for current data. GIS software that supports dynamic segmentation generally does not have any direct support for historical data, thus the control section effective and expiration dates would have to be incorporated as part of the traversal identifier.

Event data within the MACS/ROSE system is automatically synchronized when updates occur to the LRS (records are expired and created with new effective dates as needed). Keeping LRS updates synchronized with event databases external to the MACS/ROSE system is managed by several procedures. Notification of updates is sent to a standard list of data set managers, who must update their own data sets. Diagrams are produced for complex realignments. By administrative policy, corrections to milepoint errors shall be made once (or twice) a year during a specified month(s) so that other MACS/ROSE data users can make the necessary changes to their systems at the same time.

One problem with the current system is that it fragments the underlying segments in a way that presents difficult complexities for location reporting on time sheets. In rare cases, when updates occur to the MACS/ROSE LRS, the corresponding update is handled differently in the operational data set. This is the case, for example, with the maintenance management system database, where there is a strong desire to avoid LRS updates which complicate recording of locations for maintenance activities (required on time sheets). There is a desire to avoid representing a single route by multiple Segment codes, to minimize the number of equations used, and to avoid use of positive equations (which create overlaps and thus require use of new Segment codes). A complex update which involves creation of several new Segment control records (such as that described in section 4.9.8) might be performed in the maintenance database by maintaining a single record and putting a single equation at the end of the altered Segment. Other operational systems generally comply with MACS/ROSE update procedures, although others mentioned the issue of complexities in the update process on their operations.

ITD plans to migrate to a distributed RDBMS platform in the next two to three years. It is believed that many of these operational issues (e.g., time-sheet reporting, duplicate mileposts on routes, and equations) can be more easily and effectively dealt with once this migration is accomplished.

**Missouri DOT:** Historical data is fully managed in the MoDOT Travelways system such that historical conditions can be recreated for any point in time. This full management of historical data was an essential component of the information system design. The procedures have been designed and tested, but have not yet been implemented in the full TMS.

An update process has been defined and is currently in the detailed design phase. A ‘Travelway Maintenance Application’ will be developed to maintain the Travelways system’s Oracle tables.
directly from the GIS, assuring that the Oracle and GIS data are fully synchronized at all times. When any element of the LRS is updated, the affected Travelway Sections and Locations are deactivated (by setting ‘deactivate’ date fields), and new Sections and Locations are created as needed (with ‘activation’ date fields set accordingly). It is envisioned that historical alignments will be stored in the GIS as well, but it has not yet been determined how the updates will be stored (e.g., combined with current alignments in a single coverage, or in a separate coverage).

A formal system for notifying users of Travelway changes will be developed, communicating the type and nature of changes made. This may include access to a browser of a Travelway Change table, enabling users to view the sequence of changes over time (by route, by District, etc.). External users might be notified of changes by e-mail, posting to a web page, or other means. Notification will be needed to make users aware of Travelway changes, in case they are then required, due to business rules, to make changes to their data. However, for data stored within TMS, updates to locations (e.g., changing log units due to realignments) will be taken care of in the Travelways Maintenance procedure (to be developed).

**Pennsylvania DOT:** The PennDOT business procedure for historical data is set up to fully recalibrate all data, historical or otherwise, to the relative offsets as Segments are re-measured or realigned, each and every time the LRS is updated. Consequently, the location references for all on-line event data are fully rectified to the current linear referencing control. For example, if a Segments milepoints are updated with new measures, then any events that referenced the old milepoints would be updated to reference the new milepoints. The reconstruction of historical route information is technically not designed into the system. For example, if a route is turned back to a local authority, there are no provisions to collect and preserve historical data should the route ever be returned to the state. Likewise, no historical alignments are explicitly stored in the GIS data.

The business procedures used by PennDOT for synchronizing the GIS with the LRS were described previously in Figure 49, *Case Study DOT GIS Development and Use*. A well-delineated system for notification users of LRS updates is in place and considered germane to operations. Based on the information provided, end users must update their event data sets accordingly.

Historical data are available on line for five years, while other data are preserved off-line. For most foreseen business practices, most needs have been met using the existing data structure.

**Washington State DOT:** When updates are needed, automated procedures are used to realign the LRS based on construction contracts and other legal documents. Accumulated mileage values are adjusted from the point of realignment.

When updates occur to the LRS, TRIPS tables are automatically updated by the realignment process. However, TRIPS is updated daily whereas the LRS application in the GIS MADOG application is defined by the State Highway Log, which is published annually. Thus, the GIS coding of the LRS is up to one year behind changes in TRIPS. Historical alignments are not stored in the GIS data.

It can be seen that the agencies have set in place various bespoke methods to provide some minimum temporal handling of datasets. Improvements are needed in approaches and technologies to facilitate data handling.
7.5 Time Functionality for LRS

In the NHCRP 20-27(3) Panel meeting held in November 1998, the different stakeholder groups reviewed their various transportation business analytical needs. From these and case study experience listed earlier have been summarized below a possible top six key requirements for a multidimensional (that is, here, principally, “time enabled”) LRS. 12

A list of the summarized five key main requirements for handling a time-enabled LRS are:

1. **Time Stamping or Enabling of Objects**: There is a need across functional groups to “time stamp” objects, both singularly and collectively, whether they be the network objects (e.g., the highway) or the attributes of pieces of the network (e.g., a segment) or the network as a whole. This should include the capability of expressing 1D spatial objects with time, and as one moves to more complex expression of a “road”, time enabling 2D (flat map), and 3D (volumetric) expressions. For example, it may be desired that sections of highway are brought in and out of operation by time period. Accidents, road condition and other attributes exist for a particular time duration. There are a number of limitations to using time stamping as a more generic wider approach to handling time for spatial datasets, but it is a capability that is required as part of a wider approach.

2. **Time Traversal Points**: There is a need for a ‘time traversal point”, analogous to a traversal distance reference point (i.e., a time point). These location (time/space) traversal points are indications where something should be at a particular time, or, may be used as a time/location reference point. This would be useful for bus operators, who manage and monitor operations on how far in time is an object form some calibration or reference point.

3. **Multiple Time Measuring Methods**: There is a universal time reference, but there may be local time referencing schemas. Time may be measured relatively (e.g, schedule day, my watch time, “on route time”). A transit day was somewhat unique in that it may not map directly to one universal time reference day, that is, it may be 26 hours. However, all of the relative time schema should ultimately be ‘referencable’ back into the universal time reference (e.g., GMT). Different applications may wish to use versions of the local time, but then be converted across project using universal reference time as a base. The resolution of measuring time should be scalable, e.g, do analysis by one hour, week, moth, year, etc.

4. **Time entities**: There should be a number of system-supported time entities. These may have a number of predefined properties or metadata associated with them. These would include:

   1. “Traversal or route time”
   2. “Begin time”
   3. “End time”
   4. “Time interval”

12 The deductions on required functionality may not match exactly with the formal conclusions of the NHCRP panel team, when they are finally reached.
5. **Temporal Operators:** There is a need for various temporal or time focused operators. Peuquet (1999) identifies three main classes of temporal relations. These are:

1. Association between elements within a given temporal distribution at a given temporal scale
2. Combination of elements from different temporal distributions
3. Transformations between temporal scales.

The expert panel work and analysis carried out in thesis at a more disaggregate level provided the following twelve more detailed specific requirements:

1. **Time Slice:** Show me (e.g., calculate) the condition of the highway during time period x. This would be potentially usefully for highway engineers doing pavement analysis, etc.
2. **Time Period Duration Analysis:** For this piece of road, show me conditions over time x to y. Similarly, this would be potentially usefully for highway engineers doing highway analysis.
3. **Condition at time x:** Tell me what time(s) condition A occurred over section of road M.
4. **Spatial Operators time enabled:** Merge (spatial or attributes) network 1 and network 2 at time period x.
5. **Aggregate** time series based data, disaggregate time series based data
6. **Database Populate:** Populate databases in real-time, or, for a particular time period.
7. **Timepoint Analysis:** Given it is time x, what is, 1) the current vehicle location, or, 2) condition of the network
8. **Time Based Locational Estimations:** Given time x, what (should) the location be? This would be useful for transit vehicle schedulers, etc.
9. **Time Metric Conversion:** Convert from time measuring method A to time measuring method B.
10. **Time Estimation:** Update estimated arrival times given current position. This would be useful in dispatch situations.
11. **Time/space conversions:** Convert a distance and time location (e.g., 3 minutes past the 15 mile marker) to a totally time based measure (36 minutes from the start of the route) or a totally distance based measure (e.g., 10 miles form the start of the route).
12. **Time proximity:** For example, what events happened time proximate to this one?

5. **Track in Time:** A key concept that was reviewed at the NHCRP meeting was that of “navigate”. It was felt that the design of the spatial/temporal reference system has the implied functionality of being able to move within “the system” (the system being as a network). Navigation is formally defined as “movement within a spatial/temporal reference frame”. Navigate thus assumes a progression along a predefined traversal. This traversal may be defined or created, for example, by a minimum cost path, a minimum cost path that has minimum bridge clearances, a path that is the traveling salesman tour around a number of predetermined locations, etc. “Guidance” to the path

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or tour must be potentially demand responsive to meet the needs of the ITS, emergency service and other transportation communities and others.

The author of this thesis proposed the addition of the notion of “Cruising”, that is, navigating on a network without a predefined guidance. It is not certain whether this will be contained in the final recommendations of the formal NHCRP study when published. However, the concept seems to meet existent situations and reflect field need.  

Another concept – that of “latency”, in part proposed by the current author and others seemed more readily accepted. Latency can for example exist where a bus is held at a station until the train arrives or a bus is held at a particular point on a network until a time point is reached.

There are likely to be many more detailed requirements for a time enabled LRS but the above appeared to represent the core of the main requirements.

7.6 Chapter Summary and Conclusions

7.6.1 Progress Achieved

The thesis has attempted to provide a framework and vision point for the integration of the LRS field. Part of the issue with the LRS field was that the wider coherent knowledge base and “integration review” had not been undertaken and needed to be. This concern applied to the whole field, but in particular, the handling of time that seems to have lacked a focus from the viewpoint of the needs of the transportation community as a whole.

This chapter has attempted to provide a brief synthesis of time and multimodal considerations for LRS. It has done this through reference to research efforts that have been undertaken in the 1990’s, a NHCRP expert panel meeting and by drawing on some of the requirements expressed in pursuit of the Case Studies as covered in Chapter 5.

From this work, a basic set of functional requirements for time enabled and multimodal LRS have been identified. These are summarized below in Table 37.

Table 37 Summary of Time and MultiModal LRS Requirements

<table>
<thead>
<tr>
<th>#</th>
<th>1. Time</th>
<th>Level of Effort</th>
<th>2. MultiModal</th>
<th>Level of Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Time stamping</td>
<td>Medium</td>
<td>Multiple reps of same object</td>
<td>Medium</td>
</tr>
<tr>
<td>2</td>
<td>Time traversal points</td>
<td>Medium</td>
<td>Multiple Object Forms</td>
<td>High</td>
</tr>
<tr>
<td>3</td>
<td>Multiple Time Measuring Methods</td>
<td>Medium</td>
<td>Greater Model Flexibility</td>
<td>High</td>
</tr>
<tr>
<td>4</td>
<td>Time entities</td>
<td>Medium</td>
<td>Multimodal term Mapping</td>
<td>Medium</td>
</tr>
<tr>
<td>5</td>
<td>Temporal Operators</td>
<td>High</td>
<td>Multimodal Accuracies</td>
<td>Medium</td>
</tr>
</tbody>
</table>

13 Of course, police cars are called "cruisers", and could be linearly time and location tracked on a set network.
It may be possible to make individual enhancements within a reasonable period. In Table 37, "medium", represents perhaps a total of a few person months of programming effort. However, the combined and integrated set of integrated tools as system supported tools would probably represent a total of several person years programming effort (and possibly the major restructuring referred to).

7.6.2 Ten Key Observations

1. **COTS Time Extension**: The work of Candy earlier referred to (Candy, 1995) indicates that it is indeed practically possible to make extension to existing GIS COTS software to provide time functionality. (An indication is given Table 37 of the estimated level of effort to adapt and extend existing COTS GIS software, from the possible perspective of a GIS vendor.

2. **Fundamental Changes to Core Data Model**: It may be however that the fuller and generic handling of time could in optimal form require a very fundamental change in the core data structures and approaches of GIS COTS vendors.

3. **Industry Standards**: Current industry supported initiatives through OGC (earlier referred to in Chapter/section 5.10), may help address part of these issues by providing common agreed requirements and standards for interoperability.

4. **Vendor Investment**: Given such enhancements as described here seems to be the “next frontier” of GIS adaptation and extension, it seems unfortunate that vendors have seemed reluctant to make this investment to date.

5. **Transportation Community**: The transportation community may wish to ride on the coat-tails of the wider GIS community in adopting temporal operators, as the construction of such operators will in any event likely be across industry generic implementation. The problem with this approach is that no one industry has seen an absolutely critical need for time measures, and vendors have not felt it worthwhile to make their own investment.

6. **Current DOT Practice**: As reviewed in this chapter, currently DOTs have employed workable ad hoc measures to undertake temporal analyses. While these measure are hardly ideal, while the agencies are struggling to complete putting in place their core data sets, concern with temporal analyses have ultimately taken “a second seat”.

7. **Future DOT Situation**: This situation is likely to change as transportation agencies complete their core GIS development and wish to undertake more detailed analyses, including temporal, of their freshly acquired and legacy datasets.
8. **Time Functionality:** The work carried out in this chapter has indicated a set of functionality that is required with LRS activities. This includes support of, a) time stamping of objects, b) time traversal points, c) multiple time measuring methods, d) time entities, e) temporal entities (such as begin and end time), and, f) track in time.

9. **More Detailed Time Functionality:** More detailed spatial time functions would include the provision to be able to answer user queries on time slices, time period analyses, “condition at time x”, time enabling of a wider set of spatial operators, time series aggregation, populating databases based on temporal measures, timepoint analysis, time-based location estimations, time metric conversions, time estimations, time/space conversions and tools for time proximity analyses.

10. **Further Research:** Further research might focus not only on the time functionality required and the exact user preferences for this from a transportation/LRS perspective. While it is true that the longer-term provision of time-based COTS tools will benefit from a precise a description as possible of exact user needs requirements of the individual domains.

### 7.6.3 Main Conclusions

It is believed that some of the concerns that have restricted the inclusion of time within GIS the last decade have been:

1. The fact that fundamental research needs to be completed in this area
2. A resultant lack of an agreed set of industry requirements to work to
3. Possible major changes to whole technical model
4. Lack of any one client willing to pay for the addition of such tools to the core supported GIS toolbox.

It was also realized that in completing an analysis of temporal and multimodal issues, many further research topics and potential theses of a more focused nature would become more delineated. The area of multidimensional and multimodal LRS reviewed in this chapter in particular present a number of research issues that could be attractive research issues for some years to come. It appears that many of the issues identified by the NCGIA in the early 1990’s still exist. The temporal research topics are fully referenced in the NCGIA literature referred to.

Attempt to review all of these in detail has not been within the main scope of the work here. All of the identified functional requirements for time enabled and multimodal LRS need to be further delineated and researched. The aim and potential contribution of the present work was to delineate the main high-level functional requirements for LRS. In summary, more detailed analysis should be based on:

1. Much more detailed and finely structured analysis of the exact requirements of the transportation community and its information sub-communities.
2. An understanding of the progress in wider field developments, such as the handling of time in COTS databases and the fuller and further development of time enabled query languages.

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However, the analysis conducted here would indicate the three basic but fundamental observations in summary:

1. **Time stamp spatial elements**: Spatial elements at all levels in the underlying network, and all route elements, have a potential need to be time stamped. Any improved LRS design needs to include for this.

2. **Spatial temporal operators**: These need to include for the specific functionality described above (e.g., "Navigate", "locate in time", etc.).

3. **Temporal integrity**: As updates occur in the network, for example in the underlying geometry, checks to be encoded at the
   i. local level
   ii. route, and
   iii. wider area network/system level
   that the update did not affect topological, geometrical and other logical integrity checks.

The use of temporal metadata may be crucial to meeting these goals. The inclusion of temporal aspects for LRS and networks is likely to be best constructed within an overall schema for temporal COTS GIS.
Chapter References


8 Road Data Model Expert Panel

There is nothing so easy to learn as experience and nothing so hard to apply.

Josh Billings

8.1 Chapter Introduction and Purpose

This chapter briefly summarizes the activities of an Expert Panel (EP) that met to review some of the key road data models that have been proposed for possible use in network location. The participants were also asked to briefly review issues in the road data model field and then conduct a road data model “Compare and Contrast”.

Interaction with those responsible with the transportation or roadway “models” reviewed in Chapter 5 indicated that the models were produced independently, if not in something of at least a relative vacuum from one another. This was felt to be a basic but quite important observation on field research work to date. This issue practically needed addressing. A common epistemology needed to be further established, as explained in Chapters 2 and 3.

Discussions with the authors of the models indicated that while there was definitely an awareness, there had been to that date relatively little organized technical interaction, formal or otherwise, between those formulators of the models. Much of that cross-model interaction that had occurred had been informal, for example, in open session at conferences, etc. The greatest interaction has probably occurred between the creators of the Dueker-Butler model and the 20-27(2) model, since they shared in some of the same genesis (i.e., the 1994 Milwaukee LRS workshop).

The three main possible reasons for this lack of technical interaction and integration on LRS models were likely that:

1. **Funding**: Resources to support road data/LRS model development were in most cases generally limited. Resources that were provided were “project focused”, rather than, supporting some wider and longer-term mission.

2. **End goals**: Different user communities (ITS, federal agencies, software community, etc) were supporting the development of the different models or transfer standards. The models had a different foci and user needs they attempted to address.

3. **Forum**: No one forum was convenient for all the participants to interchange (with the possible exception of TRB). For example, the ITS community typically meets separately from the GIS-T community.

Therefore it was decided, as outlined in the methodology chapter (Chapter 2), to undertake a “Roadway Data Model” Expert Panel.

The general technical approach and institutional standing of the wider set of models or frameworks was earlier reviewed in Chapter 5.
8.2 Set-up of EP Meeting

This section covers the purpose and participants for the EP meeting.

8.2.1 Model Compare and Contrast

The set purpose of the EP, “Roadway Data Models” is technically a slightly larger topic than “LRS”. However, for this purposes of this present research, they were practically treated somewhat synonymously. The concern with network-based location was paramount.

The proposed purposes of the Model EP was to make a first but clear step on inter-model research and understanding. In particular, it was to review:

1. **Relative Utility**: An initial working consensus on the relative wider use of the roadway data models
2. **Role**: Some wider general view and consensus on the more precise role of the models
3. **Terminology**: Determine what different terminology was in use
4. **Cross Modal Interchange**: Gain some mutual cross understanding on the models, as this was felt not to currently exist
5. **Wider Industry Input**: Set up a workshop for wider practitioner input and review
6. **Further action**: Map out possible further research steps.

8.2.2 Support For National LRS Standards

Some effort was put into finding a funding source that might help support some drawing together of activities in this area. No current project or funding source was found was able to support participant time and formal preparation for such an activity. This perhaps indicates one, if not the, major issue with this field. In short, the lack of any national agency that sees itself having a wider remit to coordinate and support public-private initiatives in the LRS field is a major issue.

The reasons for this perhaps deserve bare clear enunciation. In overview:

1. **Public Goals**: The USDOT initiatives to date have primarily considered public agency access to public agency datasets.
2. **Private Goals**: The OMG and OGC initiatives are largely concerned with commercially funded, private sector, software building efforts and business-driven “end lines”.

There seems to have been relatively little common ground found between the public/private sides in the LRS area at least, though this concern has been also informally expressed in other spatial and standard setting arenas. The main issue is perhaps in “time to standard”, and, in reality, “time to market”. The private sector looks at the governmental processes as being slow, typically, multi-year, efforts. The private sector initiatives, as represented by OMG and OGC, wish to operate from idea conception to formal standards within approximately a one-year timeframe. This actually happened for example with the UML modeling standard. The difficulty however with the commercially driven approach is that “doing it right” may become second to “doing it” or meeting the current dictates of an initiative sponsor.
In the light of all of the above realities the authors of selected models agreed to donate time to attend such a EP meeting. BTS agreed to cover travel expenses for up to six of the EP participants and provide meeting space.

8.2.3 Participants

The practical operation of the EP meeting was placed under some limited circumstances. That is, it was:

1. A “pro bono” activity for participants in preparation participation.
2. A first formal meeting between participants.
3. One of many activities on the agendas of the busy participants. (That is, all of the invited participants did not only “do LRS”, but typically had many other research interests and activities as well).

Thus, it was realized that the EP meeting would be an initial one and would best be seen as setting the base for further and detailed work. Further work would likely be required to:

1. Further tease out the exact detailed differences between the models.
2. Seek common ground between the models.
3. Identify further work steps.

Ideally, under one analysis scenario authors or progenitors of all the models described in Chapter 5 should have been invited. However, practically it was realized that this would not necessarily be optimal as: (1) An initial EP meeting in any event was needed to better set focus for a larger meeting, and (2) The EP meeting was constrained to at most two days, and it was hoped to allow for some deeper discussion. (i.e., the three models being represented a total of six sets of incoming/ outgoing cross model comments).

In the eventuality of the time period, neither of the progenitors of the Dueker-Butler model were able to attend the EP. It was therefore decided to invite participants who were associated with three “models” shown in the column “Example 1” in Table 38. The table indicates that the term “model” is used to cover three basic forms, and the selected models cover this spectrum. An additional example of the type of model is shown in the column labeled “Example 2”

<table>
<thead>
<tr>
<th>Type of model</th>
<th>METHOD</th>
<th>EXAMPLE 1 (&quot;selected&quot;)</th>
<th>&quot;MEANS&quot; 1</th>
<th>EXAMPLE 2</th>
<th>&quot;MEANS&quot; 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Simple</td>
<td>Numbering schemes</td>
<td>BTS/NSDI</td>
<td>FTseg</td>
<td>ITS DATUM</td>
</tr>
<tr>
<td>2</td>
<td>Complex, type A</td>
<td>Transfer standard</td>
<td>STDS</td>
<td>Complex data format</td>
<td>GDF</td>
</tr>
<tr>
<td>3</td>
<td>Complex, type B</td>
<td>Rich more fully featured</td>
<td>Vonderohe model</td>
<td>Anchor points &amp; sections</td>
<td>Dueker-Butler model</td>
</tr>
</tbody>
</table>

Table 38 Roadway Model Review

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The selected models would have a US genesis and be focused on location and LRS.

It was decided to attempt to invite:

1. Model authors. In most cases, no one person was fully responsible for one model, so in most cases it was necessary to invite two people.
2. State DOT representatives familiar with LRS.
3. The FHWA GIS coordinator (Roger Petzold).

In the event, it was found extremely difficult to identify, invite and gain the attendance of a state DOT person familiar with LRS. This was felt to be a function of the following two factors:

1. **Technical Capability:** There is indeed a relative paucity of people who have a good working understand LRS in state DOT's at the current time. This itself may reflect:
   a. A “brain drain” from public to private for technical staff able to understand, implement or manage LRS efforts
   b. The fact that most DOT people “do not need LRS, per se”, but the functions it performs. LRS reengineering functions occur rarely (maybe once every 20 to 30 years in most DOTs, and may not be a topic of detailed attention at other times).

2. **Resources:** The two or three individuals identified by EP participants as likely useful contributors were not able to attend as an unsupported activity.

Roger Petzold was also unable to attend. The final set of selected and able to attend participants is shown in Table 39.

### Table 39 Roadway Data Model EP Meeting Participants

<table>
<thead>
<tr>
<th>Person</th>
<th>Organization</th>
<th>Model/Role</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Prof. Theresa Adams</td>
<td>University of Wisconsin, Department of Civil Engineering</td>
<td>NHCRP 20-27(3)</td>
</tr>
<tr>
<td>2 David Fletcher</td>
<td>GeoDigm Computing</td>
<td>The Pooled Fund Study</td>
</tr>
<tr>
<td>3 Dr. Cecil Goodwin</td>
<td>University of Tennessee, Energy, Environment and Resources Center</td>
<td>ITS Datum</td>
</tr>
<tr>
<td>4 Simon Lewis</td>
<td>Researcher</td>
<td>Workshop coordinator</td>
</tr>
<tr>
<td>5 Dr. Val Noronha</td>
<td>University of California, National Center for Geographic Information and Analysis</td>
<td>ITS Datum</td>
</tr>
<tr>
<td>6 Dr. Bruce Spear</td>
<td>Bureau of Transportation Statistics, USDOT</td>
<td>NSDI Framework</td>
</tr>
<tr>
<td>7 Bruce Wescott</td>
<td>Consultant to BTS</td>
<td>NSDI Framework</td>
</tr>
<tr>
<td>8 Prof. Al Vonderohe</td>
<td>University of Wisconsin, Department of Civil Engineering</td>
<td>The Pooled Fund study model</td>
</tr>
</tbody>
</table>
In summary, the workshop did not cover in particular the following road data models or formats:

1. TIGER files from the US Census Bureau. (These have a unique national street segment or intersection to intersection-to-intersection numbering scheme)
2. The Dueker-Butler model
3. GDF
4. SDTS
5. Other LRS or road data models not reviewed in this thesis.

The EP Meeting was conducted in the offices of BTS on March 12 and 13 1999.

Some summary consideration of the EP deliberations is given in the sections below. Focus is made relatively more on the conclusions than the detailed process of deliberation.

8.3 EP Review of Ontology and Epistemology

The EP in the time it had available did this by a review of; (1) The transportation domain being addressed, and, (2) What is the advantage of modeling? Summary of the consideration reached is given below.

8.3.1 Transportation Domain

Chapter 3 undertook a review of the viewpoints, languages and tools of the different practitioners concerned with transportation location. The EP took decided to review it's own standpoint and in the time available focused on “domains”. What was the domain or domains were the models trying to address? In short, many of the field issues appeared to be related to “domain” or “domain perspective” issues.

“Domains” may be considered as “aspects of the world”. They are an area of concern, influence or control. Our view of them may be influenced by our disciplinary or professional training, as reviewed already in Chapter 3. Domains are often defined by identifying significant objects or entities (‘things’), events, tasks and functions that exist in the world. Domain boundaries are arbitrary and generally enterprise based and defined. Domains can and do overlap.

The Road Data Domain was summarized as focusing on field:

1. **Facilities management.** This is what a public agency (e.g., a typical state DOT) would primarily focus on, as its prime remit.
2. **Transportation operations.** Private operators undertake the bulk of transportation operations. Certainly, a state DOT focuses on certain aspects of transportation operations (for example, in dealing with its own vehicle fleet).

Transportation Information Systems (TIS) dealt with managing “transportation objects”. These could be Physical objects, such as highways sections, or, Virtual objects, such as bus operating schedules or highway performance measures

Seventy percent of a DOT’s data and those of many transportation-operating authorities was noted as being “Geospatial”. Geospatial data was used for:
1. **Location referencing**, which included linear (link plus off-set), geographic (base maps) and geodetic (GPS).

2. **Spatial modeling**, which included proximity models (e.g., dynamic segmentation), and flow models (e.g., network analysis).

3. **Visualization**, which includes interactive maps and other publications.

In initial round table discussions, the EP members agreed a number of key points at the outset relating to the current LRS research and road data model adoption that appeared relevant at the present time. There was:

1. No coordinated approach.
2. Multiple national and local initiatives.
3. A lack of consensus among transportation providers and customers regarding specifications.
4. A lack of money for one national approach.
5. A lack of LRS/roadway data model technical support.
6. A lack of LRS/roadway data model operational experience.

Another review of these issues is shown in Table 40 (below). Here a set of issues were identified that in part reflected some differences in most part between LRS Modelers and Practitioners.

### 8.3.2 Why Model?

Having jointly reviewed and come to some consensus on the domain definition problem, the EP very briefly reviewed and tried to gain a working consensus on "why model" and "what is a model"?

It was noted that a model was a structure in one domain used to represent objects and events in some other domain, for the purpose of "understanding, representing, simulating or controlling it". For example, model cars help us to understand real ones through simulation. A car may in fact have many models associated with it. Some key principles about models were noted by the EP. The main eight observations are briefly summarized below:

1. **The model is not the domain.** A model is a simplification that can capture only *part of* the domain and has “model characteristics”. As noted in this thesis, the “real world” of LRS has many special characteristics many of which may not be represented in a model.

2. **Models capture only 'significant' behavior.** This is an extension of the previous point. In particular, models do not cover for all the real world vagaries and pathologies that exist in transportation networks.

3. **Models reflect the designer's point of view.** Models are typically based to a larger or lesser degree on a designer’s view of the world and not a comprehensive
Table 40 Issues Between “LRS Modelers” and “LRS Practitioners”

<table>
<thead>
<tr>
<th>#</th>
<th>Issue</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Technology</td>
<td>Was GPS obviating the longer-term need for LRS? So less need for models?</td>
</tr>
<tr>
<td>2</td>
<td>Terms</td>
<td>Road model and LRS terms used confusingly (e.g., “route”, etc.)</td>
</tr>
<tr>
<td>3</td>
<td>Differing Practitioner Viewpoints</td>
<td>Gap in the field between those concerned with conceptual modeling and those concerned with implementation</td>
</tr>
<tr>
<td>4</td>
<td>Competition</td>
<td>Appears to many practitioners that there were “competing” models to choose from and that it was difficult to resolve issues between them</td>
</tr>
<tr>
<td>5</td>
<td>LRS Reality</td>
<td>“LRS looks easy”, but was difficult in the details</td>
</tr>
<tr>
<td>6</td>
<td>Focus:</td>
<td>Retention” (memory) of LRS. It was “one of those things practitioners “got into for a period”, then “got busy on other things”, and would forget LRS issue details</td>
</tr>
<tr>
<td>7</td>
<td>Information Overload</td>
<td>A lot of alternate resource papers out there (BTS LRS resource CD – 82 papers). BUT Little synthesis to date</td>
</tr>
<tr>
<td>8</td>
<td>Vendor Offerings</td>
<td>No vendor implementations of proposed models</td>
</tr>
<tr>
<td>9</td>
<td>Exposition</td>
<td>Need for a better exposition of models generated to date</td>
</tr>
<tr>
<td>10</td>
<td>Awareness</td>
<td>“Caveat exemptor” needed. A lot of fill-in work to make core models work is needed. Need to make clear that institutional and many other factors, etc., need to be addressed, if chance of success</td>
</tr>
<tr>
<td>11</td>
<td>“Devil in details”</td>
<td>Models mainly conceptual and theoretical: relatively less focus on practice and working details. But these may be key issues in the field, etc.</td>
</tr>
<tr>
<td>12</td>
<td>Federal Lead</td>
<td>Need for a federal or national lead agency in the field, to coordinate effort, deal with deeper research issues which may be beyond any one state interest to pursue (and joint state efforts difficult practically sometimes to set up in timely and expeditious fashion; needs a sponsor)</td>
</tr>
</tbody>
</table>
user needs/perspective assessment. LRS modeler bias may be inherent. How LRS might or should work in one's view will be reflected in the model one creates.

4. **Definitions are not about things but about use.** The relationships expressed between things model define its role. In static segmentation schema the segments exist to contain and mange highway related attributes.

5. **Standard definitions are not the same as shared meaning.** The same definition may be interpreted differently, especially if the use and context are not made fully clear, or the definition does not seem to readily fit the sub-domain. For example, a highway engineer and a bus operator may understand “route” as list of linked highway segments. The highway engineer sees the list changing relatively little from year to year (his vision span); the bus operator may see it changing by hour of day.

6. **Meaning is established by context and use.** The context and use in the real world may (or in fact will) differ from that (intended) in the model. A data transfer standard may become used as a model of the real world - and seen and used that way.

7. **Data never has exactly the same meaning twice.** It may do approximately, but never exactly. All spatial data has uncertainty associated with it. A highway data collection reading of “x” may mean “x1” in association with certain metadata about that data, or “x2” is association with other metadata. For example a locational reading of 10.6,45.2 may mean 10.6,45.2 when George is taking the reading or (10.0-11.0, 44.5 to 55.5 when the trainee is taking the reading).

8. **Models are not “right or wrong”**. However, they could be more or less field or “agency useful”.

It could be argued that since each domain is distinct, so each model is distinct. Therefore, the objects in each model are also distinct and unique. However, it was noted that the whole push of national organizations such as OMG and OGC is to recognize that there may be cross-domain entities of object communalities. “Location” is for example a common component in many of the domain models, so is the concept of “network”.

The concepts of “location” and “location reference” are significant components in each of the three models considered, and yet each of them models it differently. The same is the case with the other models not represented directly in the EP session.

It was noted that there were a number of convergent high-level, organizational “architectures” for information management and control. Three key ones include:

1. **Institutional**, involving authority and control over operations and resources
2. **Procedural**, involving cooperative data and procedures
3. **Technical**, involving the ability of heterogeneous software and hardware components to communicate meaningfully.

Again, at a high-level, there are a number of technical System Architecture “patterns” or ways of structuring or implementing the IT operations. The architectures of independent, interfaced,
interoperable and integrated are very briefly outlined in Table 41. Fitting of the road data models to the above classification was then undertaken.

A central conclusion of the quick review of data models reinforced some of the research conclusions already tentatively reached in Chapter 3. That is, further work was needed in both the areas of:

1. **Ontology.** What was the exact real and full nature of the LRS phenomenon being dealt with (across the wider set of transportation communities)?
2. **Semantics.** What is the exact language used to describe the LRS phenomena in different circumstances?

In terms of the nature of the LRS phenomenon it was noted that even following the work of the transportation modal EP, further work needed to be done to solidify exactly what were the key concepts and issues. In terms of the modeling language issues raised, the following example current issues were raised:

1. **Identical terms for different concepts.** An example already quoted is of a “route” being a “time-fixed piece property”, versus, a “time-variant” entity.
2. **Different terms for identical concepts.** For example, a “polyline” may be the same as a “route” (or, it may not).
3. **Similar terms for similar concepts.** A segment and a section may be the same thing (or, they may not).

### Table 41 System Architecture and Road Data Models

<table>
<thead>
<tr>
<th>#</th>
<th>SYSTEM ARCHITECTURE PATTERN</th>
<th>SYSTEM CHARACTERISTICS</th>
<th>ROAD MODEL ARCHITECTURE</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Independent</td>
<td>Do not share any processes or data</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Interfaced</td>
<td>Simply connected systems or subsystems that can exchange information across the common boundary that they share. Share data but no processes</td>
<td>NSDI</td>
</tr>
<tr>
<td>3</td>
<td>Interoperable</td>
<td>Provide and accept services from other systems. Use the services so exchanged to enable them to operate effectively together. Share limited processes and data</td>
<td>ITS National Architecture</td>
</tr>
<tr>
<td>4</td>
<td>Integrated</td>
<td>Tightly coupled interconnection of different, highly specialized devices, subsystems or systems into a broader system providing complex functions that require close interactions between its components. Systems share many processes and data.</td>
<td>1. NCHRP 20-27 2. Dueker-Butler</td>
</tr>
</tbody>
</table>
In summary, it was felt that there was a rational justification for modeling, in terms of Explanation, the laying out of common frameworks, and, Clarification, of terms. Both the domain and the limits of roadway data modeling needed to be better understood. Modeling could help with this understanding by assisting in identifying and delineating what were some of the key questions. However, in short, it was clear that modelers sometimes gave relative “lip service” to the requirement for full understanding of the subject and the limitations of any one proposed modeling approach.

8.4 Road Model Test Case

While there was some high-level interaction “model to model”, it was felt that the distinctions between the models might become more clear on the basis of considering a common roadway data set. It appeared most of the formulatores of the models had not themselves actually directly coded up a network before. A test network was selected. The area of the current location was chosen partly because of the availability of BTS data and also because it represented a variety of roadway types, jurisdictions, etc., for the authors of the model to address. Figure 57 shows an aerial photo of the area. This photo in passing indicates the variety of potential sources that can be used for road data modeling.

Figure 57 Aerial Photo

The road study network was overlaid on a map of the area, as shown in Figure 58.
Some of the characteristics of this particular study area were that three different road governmental jurisdictions develop and maintain road databases in the same area. These were: 1) National Park Service (GW Parkway), 2) Virginia DOT (Interstate and Staten roads in VA), and 3) DCDOT (local roads in Washington, DC). Figure 60 shows network nodes that were adopted.
Tasks for network modelers included providing a means for identifying common road segments, to:

1. Indicate how to facilitate network connectivity
2. Facilitate updates to geo-spatial accuracy
3. Provide a framework for attaching attributes

In the sections below are provided some comments on the work on the common test case that was achieved in the relatively limited available time.

8.5 NSDI Approach

The technical approach of NSDI (the FGDC/BTS Roadway Data Model) was earlier summarized in Chapter/section 5.5. It was further put in context here by Dr. Bruce Spear of BTS and his consultant, Bruce Wescott. In short, they noted that the “art” of identifying common road segments was intended to facilitate:

1. Network connectivity
2. Updates to geo-spatial accuracy.

Under the NSDI approach, it was proposed that each transportation agency responsible for roads elects to become a “road database authority”. (Questions were raised to what extent different agencies in the same area would be prepared to do this, and to what extent their efforts could or would be integrated). To provide framework for attaching attributes in short, each road authority would:

1. Define road segments that best meet its business needs.
2. Posts a record for each defined road segment on a distributed national registry.

That is summarized and exampled in Table 42.

**Table 42 DC NSDI Road Numbering**

<table>
<thead>
<tr>
<th>#</th>
<th>ORGANIZATION</th>
<th>EXAMPLE STUDY ROAD</th>
<th>ROAD NUMBER</th>
<th>NUMBER MEANING</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>National Park Service</td>
<td>GW Parkway</td>
<td>00030</td>
<td>30th national authority</td>
</tr>
<tr>
<td>2</td>
<td>VDOT</td>
<td>Interstate and state roads in VA</td>
<td>51002</td>
<td>2nd designated authority in Virginia</td>
</tr>
<tr>
<td>3</td>
<td>DCDOT</td>
<td>Local roads in Washington, DC</td>
<td>11001</td>
<td>1st authority in DC</td>
</tr>
</tbody>
</table>

292
The first task was to check and assign responsibility for roads within the study area. This is done in Figure 60.

Figure 60 NSDI Road Network: Road Responsibility

The NSDI researchers described that the selected nodes of the study network would require completion of the data shown in Table 43 for use as NSDI Transportation Reference Points. It is indicated which items are “required” and which are “optional”.

Table 43 NSDI Transportation Reference Points

<table>
<thead>
<tr>
<th>#</th>
<th>NODE FEATURE</th>
<th>REQUIRED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FW-Reference-Point-ID</td>
<td>(required)</td>
</tr>
<tr>
<td>2</td>
<td>Location Description</td>
<td>(required)</td>
</tr>
<tr>
<td>3</td>
<td>Category (physical/logical)</td>
<td>(required)</td>
</tr>
<tr>
<td>4</td>
<td>Date</td>
<td>(required)</td>
</tr>
<tr>
<td>5</td>
<td>Authority-ID</td>
<td>(required)</td>
</tr>
<tr>
<td>6</td>
<td>Latitude</td>
<td>(required)</td>
</tr>
<tr>
<td>7</td>
<td>Longitude</td>
<td>(required)</td>
</tr>
<tr>
<td>8</td>
<td>Elevation</td>
<td>optional</td>
</tr>
<tr>
<td>9</td>
<td>Accuracy Statement</td>
<td>(required)</td>
</tr>
<tr>
<td>10</td>
<td>FTPseg-ID</td>
<td>(required when applicable)</td>
</tr>
<tr>
<td>11</td>
<td>FTPseg-Offset (% of length)</td>
<td>(required when applicable)</td>
</tr>
<tr>
<td>12</td>
<td>Status (planned/active/retired)</td>
<td>(required)</td>
</tr>
</tbody>
</table>

Table 44 summarizes the information likewise required for transportation segments.
The second task was to assign segment numbers for the roads within the study area. This is done in Figure 61 below for federal roads.

**Figure 61 NSDI Road Segment Numbering: Federal**
The coding of the local road network is shown in Figure 62.

Figure 62 NSDI Local Road Network

Table 45 provides a similar example for a NSDI segment.

Table 45 NSDI Framework Transportation Segments Example

<table>
<thead>
<tr>
<th>#</th>
<th>SEGMENT FEATURE</th>
<th>REQUIRED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FW-Reference-Segment-ID</td>
<td>00030.0002</td>
</tr>
<tr>
<td>2</td>
<td>From-End-Point-ID</td>
<td>00030.00003</td>
</tr>
<tr>
<td>3</td>
<td>To-End-Point-ID</td>
<td>00030.00004</td>
</tr>
<tr>
<td>4</td>
<td>Segment-Intermediate-Point ID</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Path Description</td>
<td>Memorial Bridge</td>
</tr>
<tr>
<td>6</td>
<td>Category (physical/logical)</td>
<td>P</td>
</tr>
<tr>
<td>7</td>
<td>Length</td>
<td>0.45 mi</td>
</tr>
<tr>
<td>8</td>
<td>Date</td>
<td>03241999</td>
</tr>
<tr>
<td>9</td>
<td>Authority-ID</td>
<td>00030</td>
</tr>
<tr>
<td>10</td>
<td>Accuracy Statement</td>
<td>Measured from TIGER</td>
</tr>
<tr>
<td>11</td>
<td>Status (planned/active/retired)</td>
<td>A</td>
</tr>
</tbody>
</table>
An example of the coding of a NSDI transportation reference point is shown in Table 46.

Table 46 NSDI Framework Transportation Reference Point Example

<table>
<thead>
<tr>
<th>#</th>
<th>NODE FEATURE</th>
<th>REQUIRED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FW-Reference-Point-ID</td>
<td>00030.00003</td>
</tr>
<tr>
<td>2</td>
<td>Location Description</td>
<td>Intersection of Mem. Bridge &amp; Arlington Cemetery Rotary</td>
</tr>
<tr>
<td>3</td>
<td>Category (physical/logical)</td>
<td>P</td>
</tr>
<tr>
<td>4</td>
<td>Date</td>
<td>03241999</td>
</tr>
<tr>
<td>5</td>
<td>Authority-ID</td>
<td>00030</td>
</tr>
<tr>
<td>6</td>
<td>Latitude</td>
<td>38.885500</td>
</tr>
<tr>
<td>7</td>
<td>Longitude</td>
<td>-77.059400</td>
</tr>
<tr>
<td>8</td>
<td>Elevation</td>
<td>-</td>
</tr>
<tr>
<td>9</td>
<td>Accuracy Statement</td>
<td>Digitized from TIGER</td>
</tr>
<tr>
<td>10</td>
<td>FTSeg-ID</td>
<td>-</td>
</tr>
<tr>
<td>11</td>
<td>FTSeg-Offset (% of length)</td>
<td>-</td>
</tr>
<tr>
<td>12</td>
<td>Status (planned/active/retired)</td>
<td>A</td>
</tr>
</tbody>
</table>

A key point to note with coding the NSDI framework is with regard to *implicit* versus *explicit* connectivity. There is:

1. Implicit connectivity – *FTSeg* share a common anchor point
2. Explicit connectivity – *FTSeg* connected through connectivity information in the FTRP record.

As exampled in Figure 63 and Table 47, segments (here, segments 2 and 3) can connect to a segment (here, 1) without breaking it (i.e., it being necessary to create new segments along the length of segment 1). The information is implicitly stored as shown in Table 47.

Table 47 NSDI Implicit versus Explicit Connectivity II

<table>
<thead>
<tr>
<th>FTRP ID</th>
<th>CONNECTS TO FTSeg ID</th>
<th>% LENGTH</th>
<th>MEASURED FROM REF POINT ID</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FTRP_2</td>
<td>60.00%</td>
<td>FTRP_1</td>
</tr>
<tr>
<td>2</td>
<td>FTRP_3</td>
<td>95.00%</td>
<td>FTRP_1</td>
</tr>
</tbody>
</table>
Table 48 and Table 49 example the completion of records with implicit topology.

Table 48 Example NSDI Transportation Reference Points

<table>
<thead>
<tr>
<th>#</th>
<th>NODE FEATURE</th>
<th>REQUIRED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FW-Reference-Point-ID</td>
<td>11001.40023</td>
</tr>
<tr>
<td>2</td>
<td>Location Description</td>
<td>Intersection 23rd St, NW &amp; Constitution Ave., NW</td>
</tr>
<tr>
<td>3</td>
<td>Category (physical/logical)</td>
<td>P</td>
</tr>
<tr>
<td>4</td>
<td>Date</td>
<td>03241999</td>
</tr>
<tr>
<td>5</td>
<td>Authority-ID</td>
<td>11001</td>
</tr>
<tr>
<td>6</td>
<td>Latitude</td>
<td>38.891902</td>
</tr>
<tr>
<td>7</td>
<td>Longitude</td>
<td>-77.049862</td>
</tr>
<tr>
<td>8</td>
<td>Elevation</td>
<td>-35.4 ft msl</td>
</tr>
<tr>
<td>9</td>
<td>Accuracy Statement</td>
<td>Digitized from 0.2 m DOQ</td>
</tr>
<tr>
<td>10</td>
<td>FTSeg-ID</td>
<td>11001.4231</td>
</tr>
<tr>
<td>11</td>
<td>FTSeg-Offset (% of length)</td>
<td>48.62</td>
</tr>
<tr>
<td>12</td>
<td>Status</td>
<td>A</td>
</tr>
<tr>
<td></td>
<td>(planned/active/retired)</td>
<td></td>
</tr>
</tbody>
</table>
Table 49 NSDI Transportation Segments Example

<table>
<thead>
<tr>
<th>#</th>
<th>SEGMENT FEATURE</th>
<th>REQUIRED</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>FW-Reference-Segment-ID</td>
<td>11001.4002</td>
</tr>
<tr>
<td>2</td>
<td>From-End-Point-ID</td>
<td>11001.40023</td>
</tr>
<tr>
<td>3</td>
<td>To-End-Point-ID</td>
<td>11001.40051</td>
</tr>
<tr>
<td>4</td>
<td>Segment-Intermediate-Point_ID</td>
<td>-</td>
</tr>
<tr>
<td>5</td>
<td>Path Description</td>
<td>Constitution Ave. NW from 23rd St. to Virginia Ave.</td>
</tr>
<tr>
<td>6</td>
<td>Category (physical/logical)</td>
<td>P</td>
</tr>
<tr>
<td>7</td>
<td>Length</td>
<td>0.504 mi</td>
</tr>
<tr>
<td>8</td>
<td>Date</td>
<td>03241999</td>
</tr>
<tr>
<td>9</td>
<td>Authority-ID</td>
<td>11001</td>
</tr>
<tr>
<td>10</td>
<td>Accuracy Statement</td>
<td>Measured from DME</td>
</tr>
<tr>
<td>11</td>
<td>Status (planned/active/retired)</td>
<td>A</td>
</tr>
</tbody>
</table>

It appeared that this was the first time that NSDI had been field-coded. It was hoped that the above brief working example above would provide a useful example. Further details on coding of the NSDI framework are in the detailed 100-page reference manual.

8.6 NCHRP 20-27(2) LRS Data Model

It was noted that at the time of the seminar there had been relatively limited attempt to prior date to actually implement the 20-27 model in the field. Professors Alan Vonderohe and Professor Theresa Adams of the University of Wisconsin presented the NCHRP 20-27(2) model application.

They noted that now the agency LRS person or their consultant/modeler must decide on:

1. Datum Objects  
   How Many?  
   Where?
2. Reference Objects  
   How Many?  
   Where?
3. Measurements among them  
   What to Measure?  
   With What Accuracy?  
   With What Technology?

The modeler must decide all of these in a least-cost framework. The importance of anchor points and anchor sections to the 20-27 approach has been discussed earlier (see NCHRP data model, Figure 39, page 174).
The authors of the NHCRP 20-27 approach believed that the creation of the model should be driven by business data needs. The objectives of the model can be achieved by reverse engineering end-user requirements for accuracy in business data. It was stated that the high-level requirements are driven by business functions. Considerations of the NHCRP model might also be inputs to referencing system design process.

The actual design method to set up the model base involves geodetic engineering design techniques (survey) to determines configuration of the datum and reference objects. The techniques involve an accounting for error propagation. The method includes redundant measurements and analytical processing of the results to provide possible estimates for datum values and their levels of certainty (i.e., statistical reliability).

A key task with the NHCRP approach was deciding where to place anchor points and anchor sections. This is completed below for the study area in Figure 64. These form the survey/cartographic base of the network.

Following this, nodes and kinks need to be assigned to the network. Nodes are defined as zero-dimensional objects that are topological junctions of two or more links or an end point of a link. Links are defined as a topological connection between the two ordered nodes. 36 nodes and 43 links were defined for the network. These are subsequently shown in Figure 65.

Figure 64  NHCRP Anchor Nodes and Sections
Traversals and reference points now were to be defined. Traversals were defined as an ordered set of directed, but not necessarily connected set of whole links. A Traversal Reference Point is defined as zero dimensional location along a traversal that is used to reference events along a traversal. An example is shown in Figure 66.

Figure 65 NHCRP Nodes and Links

NCHRP 20-27(2)
Nodes 36
Links 43

Figure 66 NHCRP Traversal and Traversal Reference Points
A point event is a zero dimensional phenomenon that occurs along a traversal and is described in terms of its attributes in the extended database. A Linear Event is a one-dimensional phenomenon that occurs along a traversal and is described in terms of its attributes in the extended database. Examples of these are shown in Figure 67.

**Figure 67  NHCRP Point and Linear Events**

The NHCRP model allows for potentially more than one cartographic representation to be made for a Linear Referencing System. Figure 68 shows one cartographic representation.

In summary, the purpose of the NCHRP 20-27(2) LRS Data Model was sharing and integration of linearly-referenced data at a known and controllable level of accuracy. The field design as for the example here should be driven by accuracy requirements for business data. This should be derivable from an examination of business functions. The NHCRP 20-27(2) approach is based on a geodetic engineering design method. This was felt to be a least-cost configuration for a referencing system guaranteed to meet accuracy requirements at a specified level of certainty.
8.7 ITS Datum

Information on the ITS datum was provided by Dr. Val Noronha. The ITS Datum was designed to deal with the magnitude and scope of the ITS locational problem. The ITS Datum was designed as a user service to an identified 30 user sub-communities (e.g., EMS, transit, CVO, etc.). Tracking vehicles in real time and the ability to send ISP messages to vehicles were main issues. Other big concerns include safety and credibility.

The difficulty of the location address problem was shown using examples from Santa Barbara county showing freeway, residential and remote

It was noted that potential location expressions in ITS included:

1. Coordinates (latitude - longitude, UTM)
2. Cross streets (Birch between Ash & Cedar +δ)
3. Civic addresses (1725 Birch)
4. Linear referencing — identifier +δ
5. Landmark referencing
6. Custom grid references (e.g., Thomas Bros)
7. IDs for nodes/links
8. Hybrids (ILOC, XSP, LX-100)

The ITS Datum was:
1. A set of reference points that is agreed upon
2. A set of distances between points, that is agreed upon
3. Location by reference to corrected coordinates and the points themselves, by ID

The art of ITS Datum point selection was discussed. It involved the consideration of:

1. **Density**: how many points?
2. **Selection**: which intersections?
3. **Siting**: where in the intersection?
4. **Precision** (m, dm, mm) and **accuracy** (± ?m).

Intersections for the ITS Datum need to be:

1. Unambiguously identifiable across digital maps
2. Represent decision points when driving
3. Densest where consequence of coordinate error is greatest: curves, especially ramps
4. Fewer in regular “gridded” areas

The tolerance for the siting of ITS datum points was discussed. The straw man specifications for this are shown in Table 50.

### Table 50 ITS Datum Point Tolerances

<table>
<thead>
<tr>
<th>Year</th>
<th>Highway Type</th>
<th>Lateral</th>
<th>Longitudinal</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000</td>
<td>Open divided highway</td>
<td>30m</td>
<td>50-100m</td>
</tr>
<tr>
<td></td>
<td>Street Interchange</td>
<td>5m</td>
<td>50m</td>
</tr>
<tr>
<td>2010</td>
<td>Open divided highway</td>
<td>2m</td>
<td>10-20m</td>
</tr>
<tr>
<td></td>
<td>Street interchange</td>
<td>2m</td>
<td>5m</td>
</tr>
<tr>
<td>2020</td>
<td>Open divided highway</td>
<td>0.5m</td>
<td>1m</td>
</tr>
<tr>
<td></td>
<td>Street Interchange</td>
<td>0.5m</td>
<td>1m</td>
</tr>
</tbody>
</table>

The implications for this included that interstate intersections would need to have multiple point associated with them to define them. The main issue with the ITS datum then became the siting of ITS datum points. These were defined for the study area as defined in Figure 69.
ITS datum links were defined between the ITS nodes. These are shown in Figure 70.

**Figure 70 ITS Datum study Area Links**
Summary business principles that drove the ITS datum were:

1. Benefits must justify costs. There was an effort for example to express accuracy considerations in cost terms.
2. The exercise may be undertaken with a data set with shape points, not just the nodes and links.
3. There may be spin-off benefits, e.g., possibly an improved Census Bureau TIGER file data.

The exercise indicated that there might be “borrowable components” from other model efforts:

1. *Length from 20-27:* Further work needed to be done to see if compatible with 20-27 principles. ITS Datum nodes must almost always be at intersections.
2. *IDs from NSDI:* This would technically work, but may not be compatible with NSDI evolutionary timetable.

### 8.8 Chapter Summary and Conclusions

A workshop on the results of the two-day meeting was given shortly thereafter at the 2000 AASHTO GIS-T Symposium (Lewis and Williams, 1999).

#### 8.8.1 Progress Achieved

A summary review of the genesis, background and operation of the transportation road data models was made. The results of this are summarized in Table 51, and cover eight main aspects. Clearly, the comparison was a preliminary one, but was useful in further establishing some key points. Two key observations could now be more clearly made:

1. The models were very clearly tied to the particularly user group sponsoring the research. There had been no cross-model comparison or inter-working. The future basis for this was now at least put in place.
2. In any event, it was unlikely that one model would readily fit all needs the current models examined were ascribed to.
<table>
<thead>
<tr>
<th>ISSUE</th>
<th>NSDI</th>
<th>NHC RP 20-27(2)</th>
<th>ITS Datum</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Problem(s) Addressed</td>
<td>1. Road network databases used for different applications (Carto., LRS, network path-building) 2. Federal agencies not maintain a national road database</td>
<td>1. Meet common needs of as many Stakeholders as possible; form generic core that can be extended to specific applications. 2. Facilitate sharing of LRS data across business units 3. Data have a known and controllable level of accuracy</td>
<td>1. Data “interfaceability” for ITS applications 2. Data interoperability within centers 3. A common frame of reference for registration of prop vendor database 4. Facilitate local agency efforts</td>
</tr>
<tr>
<td>2 Alternate solutions</td>
<td>1. “Do nothing” 2. Let public sector build the data 3. NSDI</td>
<td>Ditto</td>
<td>Ditto Adopt GDF?</td>
</tr>
<tr>
<td>3 Issues in Sharing road network data</td>
<td>Networks share multiple applications Applications segment networks differently Database maintenance</td>
<td>Ditto</td>
<td>Ditto</td>
</tr>
<tr>
<td>4 Domain</td>
<td>Developers and users of transportation databases, NSDI transportation layer To facilitate sharing of cartographic data</td>
<td>Federal, state, MPO, transit agencies Scope is linear “Not a specification”</td>
<td>ITS is a SYSTEM with vehicle, interface and Center components</td>
</tr>
<tr>
<td>5 Functional Requirements</td>
<td>1. Independent of any cartographic scale or topological network 2. Identifiers remain stable 3. Minimise additional burden on database developers 4. Facilitate integration of networks from different sources</td>
<td>Vast amounts of Transport data; Many LRM's, network reps., carto reps Users / Applications need not have the Same Methods, Networks, or Spatial Databases to Share Linearly-Referenced Data; One Datum: Application Indp'ndnt Support for Locate, Position, Place and Transform</td>
<td>1. Need to include (varying) accuracy level with data 2. Need fast data access</td>
</tr>
<tr>
<td>7 Applicability</td>
<td>In particular, federal and local agencies (?)</td>
<td>In particular, State DOT’s</td>
<td>ITS applications</td>
</tr>
</tbody>
</table>
In short, it was seen that the existing road data models are *different solutions to similar problems*, as summarized in Table 52 and Table 53.

**Table 52 Road Data Model: Main features Compare and Contrast**

<table>
<thead>
<tr>
<th>#</th>
<th>ASPECT</th>
<th>NSDI</th>
<th>ITS DATUM</th>
<th>NHCRP 20-27</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Domain</td>
<td>Geospatial data</td>
<td>Traffic operations</td>
<td>Facilities management</td>
</tr>
<tr>
<td>2</td>
<td>Purpose</td>
<td>Data fusion</td>
<td>Systems interoperability</td>
<td>Systems integration</td>
</tr>
<tr>
<td>3</td>
<td>Institutional Scope</td>
<td>Federal clearinghouse</td>
<td>Systems interoperability</td>
<td>Single DOT enterprise</td>
</tr>
<tr>
<td>4</td>
<td>Key Feature</td>
<td>Permanent feature identity</td>
<td>Geodetic location w.r.t. to known point</td>
<td>Control section with known error</td>
</tr>
<tr>
<td>5</td>
<td>Essential Attributes</td>
<td>Feature ID</td>
<td>Node location</td>
<td>Section length</td>
</tr>
<tr>
<td>6</td>
<td>Status</td>
<td>Standard Under development</td>
<td>Standard under development</td>
<td>Published, several pilot implementations</td>
</tr>
<tr>
<td>7</td>
<td>Span of influence</td>
<td>Clearinghouse</td>
<td>Multiple enterprises</td>
<td>Single enterprise</td>
</tr>
<tr>
<td>8</td>
<td>Primary Purpose</td>
<td>Map interoperability</td>
<td>Vehicle/center interoperability</td>
<td>LRM interoperability</td>
</tr>
</tbody>
</table>

**Table 53 Road Data Model Comparison: Technical Features**

<table>
<thead>
<tr>
<th>#</th>
<th>ASPECT</th>
<th>NSDI</th>
<th>ITS DATUM</th>
<th>NHCRP 20-27</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Requires New Data</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes,</td>
</tr>
<tr>
<td>2</td>
<td>Requires additional fieldwork</td>
<td>No</td>
<td>Yes, measure point locations</td>
<td>Yes, measure section lengths</td>
</tr>
<tr>
<td>3</td>
<td>Requires GIS base map</td>
<td>No</td>
<td>No</td>
<td>No</td>
</tr>
<tr>
<td>4</td>
<td>Primary 0-cell feature. (Primitive Site Object)</td>
<td>Framework Transprt. Ref Point (FTRP)</td>
<td>ITS datum node</td>
<td>Site (specialized as Reference Point, Node &amp; Anchor Pnt)</td>
</tr>
<tr>
<td>5</td>
<td>Primary 1-cell (Primitive Section Object)</td>
<td>Framework Transportation Segment (FTseg)</td>
<td>ITS Datum Link</td>
<td>Section (specialized as Link and Anchor section)</td>
</tr>
<tr>
<td>6</td>
<td>Architecture: Geodetic Location</td>
<td>Yes</td>
<td>Yes</td>
<td>Optional</td>
</tr>
<tr>
<td>7</td>
<td>Nationally Unique ID's</td>
<td>Yes</td>
<td>Yes</td>
<td>Not required</td>
</tr>
<tr>
<td>8</td>
<td>Control ID error</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>9</td>
<td>Control 2-D error</td>
<td>No</td>
<td>Yes</td>
<td>No</td>
</tr>
<tr>
<td>10</td>
<td>Network topology supported</td>
<td>No segment list</td>
<td>Yes</td>
<td>Yes, indirectly</td>
</tr>
<tr>
<td>11</td>
<td>Precision</td>
<td>Micro degree lat/long</td>
<td>Varies according to site</td>
<td></td>
</tr>
<tr>
<td>12</td>
<td>Logic for Point Selection</td>
<td>Authority or legacy</td>
<td>Optimal navigation support</td>
<td>Control of linear error</td>
</tr>
</tbody>
</table>
8.8.2 Ten Key Observations

1. **Purpose of Road Data Models**: The road models seemed to take a different cut on two basic things:
   a. **Domain**: What exactly is the transportation domain?
   b. **Components**: How do, “how do we chunk up” the national infrastructure of roads?

2. **View on OO**: OO is “more than just another data format”. It requires in short a change in thinking. Many practitioners who have started using OO techniques have said that it has taken a full year to make this change. Many objects, including objects in the transportation domain, have complex behaviors. It is necessary to understand the behavior of objects properly before one can model them.

3. **Nature of Transportation Objects**: A transportation object can be both **real** (e.g., roadway, bridge) and **virtual** (e.g., node, link and path).

4. **Multiple Geometries**: With OO, feature objects can more readily have **multiple geometries**. In GIS until today, features have typically had one set of geometries associated with them.

5. **Advantages of OO**: OO provides opportunities for, a) improved data modeling and simulation of real-world spatial phenomena with complex interdependencies, and, b) data generalization.

6. **Diagramming Methods**: The lack of a common diagramming method to date had been a limitation. UML offers a way forward past this particular problem.

7. **Commercial Foci**: OMG and OGC were focusing on particular sub-areas of the transportation field that their primary sponsors had identified.

8. **Training and Education**: It is possible to build something poorly in any paradigm, including OO. However, the best results in any paradigm come with training and education.

9. **Standard Transportation Features**: Much still had to be done in transportation to develop transportation object oriented data structures.

10. **Future research - Start with the Network**: Thinking about OO approaches to LRS could be facilitated by first thinking on OO data structures for transportation networks.

8.8.3 Main Conclusions

A major overall conclusion drawn out of the workshop was that all the senior presenters seem to agree the potential of OO concepts applied to transportation spatial analysis was significant, but had not been practically advanced to date by theoretical development or well-worked (or even
marginal or partial) example. The work here was an important first step – but only that and needs to be followed up by subsequent research. This needs to more fully tease out the more detailed technical overlaps and possible interactions of the models.

These issues ultimately seem more tractable than the issue that the road data models have different institutional sponsors. Institutional issues are briefly reviewed in this next chapter.
8.9 Chapter References


*Experience is the mother of science.*
Proverb
9 Institutional Issues Related to LRS

Already, a network etiquette, or "netequiетte" is evolving. As the information highway becomes society's town square, we will come to expect it to conform to our cultures mores. There are vast cultural differences around the world, so the highway will be divided into different parts, some dedicated to various cultures, and some specified for global usage.

The Road Ahead. Bill Gates.
(Referring here first to IT and communication networks)

9.1 Chapter Introduction and Purpose

This thesis has focused largely on technical issues related to LRS. Experience to date has shown the principal factors in successful GIS-related activities are institutional rather than technical. There is however at least some clear body of more solidly-based research work on GIS institutional issues (e.g., Azad, 1998, Evans, 1997). This thesis therefore took as its prime focus what it felt to be a relatively un-addressed attempt to gain a wider and more solid research setting, context and set of working recommendations for LRS. It was however noted:

1. The clear record of particular importance of including institutional considerations in enterprise-wide spatial data endeavors
2. The practitioner focus of this thesis, where a "holistic", "real world", approach and working context was sought

Thus, a place of prominence near the Conclusions of this thesis has been included for this topic. It mainly draws on both the research work of others, as well as the many GIS and transportation activities listed in the Technical Acknowledgements to this thesis. The intent here is to give good reference and a working frame.

Clearly, there have been several DOT efforts at topics such as LRS, which have resulted in projects funded to several hundred thousand dollars, being aborted. The usual reasons for these were not that "the technology did not work" or that the technology could not be made to work. Rather, the problems may be traced to "institutional issues". Unfortunately, the case studies surrounding many of these aborted projects have not been written and will not be written.

"Institutional issues" may be defined as "the non-technical impediments to the success of the ultimate deployment of a technology" (Volpe, 1994). This of course is possibly a somewhat pejorative definition as there may indeed be very valid and rational concerns why a technology should not be implemented (at least as proposed) because of very valid institutional concerns. In reality, there will not be an effort to apply technology unless there is at least some rational basis that some form of it would give expected benefits. There may well be an issue of needing to redesign or refocus the technology to better fit and reflect institutional concerns.

Institutional issues may be broadly considered under four headings:

1. Organizational
2. Regulatory
3. Human resources
4. Financial


This does not of course mean that the technology does not have to be “best set-up”, or implemented. Indeed, lack of deeper understandings on the appropriate wider design and set-up of GIS may be key determinants of organizational acceptance and take-up. However, research to date, as exampled through the work of Azad (1998), the research work carried out for the FHWA DP113 Integrated Transportation Information Systems course (FHWA, 1998), and by others, indicates that other institutional factors are far more critical in likely organization acceptance and successful implementation. These factors include to the gaining of top management support, the placement of responsibility for the function in the organization, and training and education of staff.

As far as literature surveys to date have indicated, as relatively little more formal research has been conducted on LRS, no previous research has been previously been conducted specifically on LRS institutional or organizational issues. Certainly, there has been work on institutional issues relating to for example:

1. Information Technology (Lucas, 1994),
2. GIS (Campbell, 1998) and
3. ITS (Volpe, 1994).

As noted, experience with GIS-related issues in the field (which LRS maybe taken closely with) is that institutional issues may be in the field “at least 50% of the problem”. Proceedings of the AASHTO GIS-T Symposium certainly emphasize the importance of institutional issues. Certainly, using ten years of personal experience, this practitioner would attest to that observation after the execution of 42 GIS-T projects in over 20 states. If on institutional issues, a briefest summary remark on ten year’s experience may be made it would be this. One felt that to do GIS/LRS one should have been a Harvard man (“an institutional man”), rather than, a MIT man (“a technical man”). This chapter thus attempts to briefly reference some of the wider body of work relating to institutional issues that relate to LRS. It does this by a brief review of the general issue of dealing with technological change (which adopting new LRS practices might imply) and consideration of institutional factors that may relate to LRS from an agency and national perspective.

This chapter is also done in part towards a setting for the wider drawing together of the body of work here. Strong general reference has been made to the literature throughout this thesis. While this chapter draws on the work of Evans, Azad and others, as previously noted, it also draws on the experience of presenting workshops on LRS and related issues to transportation agencies in “sleeves-up mode” on over 50 occasions between 1990 and 1998, as well as many working projects where LRS related concerns were identified as foundational to the overall project.
9.2 Agency Level Consideration

9.2.1 Dealing With Agency Level Change

One key wider institutional issue there may face today and in particular with dealing with information technology related matters (which in implementation LRS largely focuses) is change — and, more so, dealing with the pace of change.

There have been many several major fundamental organizational and management biases or foci evident in handling change in human history. These are very briefly summarized in Table 54. The table shows three key attributes of management activity — people, process and technology. A finer review of the detail on the cycles is not made here. The key point is that the cycles of dominant management or institutional paradigms are growing very short — 2,000 years for the Crafts and Guilds paradigm, to 5 or 10 years for "a cycle" or less, currently.

The related point in terms of LRS is that in state DOTs is that business practices by any historical precedent are changing fast and quickly. Over the last 30 or 40 years fairly regularized means and ways of doing things became strongly established. A change to a new paradigm, along with changes in all the other paradigms that are occurring currently in the "information age", may represent a very significant additional change. So much so, sometimes organizations DOT's included may deliberately decide to skip a generation of technology change and catch the next technological or business process change wave. Most DOT's tend to be fairly conservative and while providing workshop to them it was often heard that they did not wish to be on the cutting edge (even, implied, the trailing edge). Thus, change itself may need to be managed. A whole field of "change management" and business process change has grown up.

Table 54 Organizational and Management Approaches in History

<table>
<thead>
<tr>
<th>Era</th>
<th>People</th>
<th>Process</th>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>2000 BC</td>
<td>Crafts and Guilds</td>
<td>Emphasized</td>
<td>Minimal</td>
</tr>
<tr>
<td>1850</td>
<td>&quot;Taylorism&quot;</td>
<td>Minimal</td>
<td>Emphasized</td>
</tr>
<tr>
<td>Late 1800's</td>
<td>Industrial</td>
<td>Minimal</td>
<td>Important</td>
</tr>
<tr>
<td>1900's</td>
<td>Human Resources</td>
<td>Emphasized</td>
<td>Minimal</td>
</tr>
<tr>
<td>1970</td>
<td>Total Quality</td>
<td>Important</td>
<td>Emphasized</td>
</tr>
<tr>
<td>1990</td>
<td>Bus Proc Re-engineering</td>
<td>Minimal</td>
<td>Important</td>
</tr>
<tr>
<td>2000 &amp; beyond</td>
<td>Growth Imperative</td>
<td>Emphasized</td>
<td>Important</td>
</tr>
</tbody>
</table>

Such is the practical issue of dealing with change that the FHWA course on information technology taught by the author from 1994 to 1999 partly changed into a course on "change management" and "IT-related Change". Space is not taken to fully detail here the different institutional approaches that are available. NHCRP Report 371 deals with "State Departments of Transportation: Strategies for Change". However, the approaches indicated below in Table 55, in effect, offered themselves to DOT management as encompassing as different change management approaches — at the agency, strategic level. In another view, the difficulty of dealing with wider agency change encouraged or necessitated the adoption of some wider
agency paradigm for dealing with change. Information technology was both a response and a cause of change.

### Table 55 DOT Enterprise-level IT/Change Approaches


<table>
<thead>
<tr>
<th>Focus</th>
<th>Level of Effort</th>
<th>Example DOT</th>
<th>“Do everything”</th>
</tr>
</thead>
<tbody>
<tr>
<td>“Do Nothing”</td>
<td>None or low</td>
<td>Several</td>
<td></td>
</tr>
<tr>
<td>Total Quality Management</td>
<td>Organization</td>
<td>Low</td>
<td>Arizona, Michigan</td>
</tr>
<tr>
<td>Practical / Standards</td>
<td>Standards and data</td>
<td>Medium</td>
<td>Florida, Michigan</td>
</tr>
<tr>
<td>Information Engineering</td>
<td>Data and technology</td>
<td>Medium</td>
<td>Wisconsin, Michigan</td>
</tr>
<tr>
<td>Data Warehousing</td>
<td>Data and technology</td>
<td>High</td>
<td>Maine, Michigan</td>
</tr>
<tr>
<td>Business Process Reengineering</td>
<td>Business process</td>
<td>High</td>
<td>Texas, Michigan</td>
</tr>
</tbody>
</table>

These different paradigms had associated with them a wider set of tools, languages and management approaches for dealing with change and information technology and business process change and adaptation.

### 9.2.2 Case Studies Reviewed

The four case studies provide ample experience and examples that each DOT has its own institutional way of dealing with particular issues. Different solutions support different levels of functionality, and each solution has its own basis in the context of each agency’s business practices.

From a broader perspective, one might ask why these four DOTs have been successful with regard to their use of linear referencing. Largely, their success can perhaps be attributed to institutional structure and support. Consideration is focused here on mainly one aspect — institutional placement of LRS responsibilities. As shown in Table 56 below, each case study DOT assigns responsibility for managing and maintaining LRS and GIS operations to specific offices. In two instances the GIS and LRS responsibilities are in the same organizational unit; in two they are not. All are not directly part of the DOT IT unit. This reflects the fact that LRS has to date has first been viewed as a field or “Planning” issue, rather than, an IT or a “data management” issue first. (Approaches later proposed in this thesis will reflect a refocusing on this issue).

By quick examination of this table, it can been that in the Case Study DOTs by regard to current responsibility placement, LRS activities may be regarded as a Planning or data management issue. This is reflected also in other US DOT’s.
Table 56 Institutional Responsibility for LRS & GIS Operations

<table>
<thead>
<tr>
<th>ITD</th>
<th>MoDOT</th>
<th>PennDOT</th>
<th>WSDOT</th>
</tr>
</thead>
<tbody>
<tr>
<td>Office responsible for the agency’s LRS</td>
<td>MACS/ROSE unit of the GIS Section, Planning Division</td>
<td>Travelways Section, Office of Transportation Management Systems</td>
<td>Bureau of Maintenance and Operations</td>
</tr>
<tr>
<td>Office responsible for the agency’s GIS</td>
<td>The GIS Section, Planning Division</td>
<td>GIS Section, Office of Transportation Management Systems</td>
<td>Roadway Data Section, Planning and Programming Service Center</td>
</tr>
</tbody>
</table>

Linear referencing poses a particular challenge to data management in that its use is generally widespread in separate offices and operational systems, yet it is subject to updates over time. Likewise, integration with other location referencing methods is increasingly important for gaining the greatest value from an agency’s information resources. Effective management of an enterprise LRS requires clear recognition of the essential role of location referencing to data integration, and adequate institutional support for coordination and maintenance of the system.

Management of an enterprise LRS has traditionally been aligned with a central information systems office, and often with a mainframe-based roadway characteristics database. In contrast, GIS is often associated with a planning office, which may take on responsibility for implementing and maintaining the agency’s linear referencing in GIS. This separation of responsibility may complicate coordination and synchronization of updates between the LRS and GIS. Although workflow practices such as those used by PennDOT (section) can be developed to address this issue, experience elsewhere has shown that this general approach is not fully reliable. For many transportation agencies, management of LRS and GIS operations will likely be more tightly integrated in the future, if not merged altogether. Indeed, operational maintenance of the LRS may be best managed by a GIS application with the benefits of its graphical interface. The Missouri DOT’s Office of Transportation Management Systems exemplifies an organizational structure where a single office is responsible for managing the LRS and the GIS, as well as the operational databases by which they are used.

Location of responsibility is just one aspect of institutional arrangements that can be considered and were not the first concern of the case studies undertaken. A wider framework is required to best conduct such an analysis. The potential provision of one of these is reviewed in the next subsection.

9.2.3 Improved Agency Methods I: The Zachman Framework

ITIS may be defined as the “combination of all transportation related information systems developed as part of a single information systems architecture in a framework where people and information technology working together to improve transportation solutions”. (FHWA, 1998). LRS is practically a key part of this architecture as it is often the key indexing means for
integrating many of the operational databases within a state DOT. For example, LRS thus becomes key in creating a state DOT Data Warehouse. Maine DOT has for example built a Data Warehouse heavily focused around its use of LRS (in fact, LRS is the indexing mechanism for typing all of the DOT data together). Very few state DOT’s have truly yet adopted an enterprise-wide architecture approach, but a few have or are moving to that at least that vision.

In attempting to build information systems based on methodologies such as LRS, architectures may be put in place to order, arrange and set-up the set of information artifacts so that institutional needs are best met. Frameworks or methods are required that closely integrate technological and institutional change planning and design.

The Zachman Framework is the best-known generic enterprise architecture for implementing enterprise information technologies that LRS would sit within (Inmon, et al, 1997). The framework addresses:

1. Technology/network (What/where?)
2. Business process/work methods (How?)
3. Organization/people (Who?)
4. Data (What?)
5. Motivation (Why?)
6. Time (What?)

Technology is thus just one of the six components of the Zachman framework. Analysis of technology may be done by the consideration of technology architecture, performance, standards, usability and vendor. For example, will my LRS work in database technology A, and if yes, what is the performance, standards, etc. Analysis of business process may consider aspects such as business functions (e.g., engineering, accounting, etc.), processes to support those functions (e.g., activities to meet the functional need). It may also consider data flows (at a high level – for example in and out of the organization) and performance measures. For example, “safety management” may be a DOT function and accident analysis (using LRS) maybe a activity carried out to meet this need. The elements are interlinked, as shown in Error! Reference source not found. (which is a simplified version of the framework).

Consideration of organizational issues may for example include:

1. Goals and objectives, at both the enterprise and work group level
2. Responsibilities to meet goals and objectives
3. Activities to meet organizational responsibilities
4. Communications, both internal and external
5. Skills, including for example an assessment of organizational skills to adapt or learn new methods or technology.

An assessment of organizational matters can also review management philosophy, management support, agency culture, agency strategy, internal and external politics, training and education needs, resource needs (e.g., staffing, equipment) and reorganizing agency structure. Thus, for example, an assessment of the likelihood of success of adopting a new LRS approach would have to consider existing data handling and database skills, actual available time from other tasks, career incentives, etc.
Figure 71 Integrated Transportation Information System

Based on Lewis, 1997
Data is another focus area for the Zachman framework. It may include considerations of definition, standards, storage and collection methods, clean-up efforts and costs, structure, metadata, ownership, and security. For example, who are the current owners or users of linearly referenced data in the DOT?

Two other areas of concern are Motivation and Time. Motivation covers a need to gain a understanding why the business or organization is conducted and may cover all components previously mentioned. Time (when?) may cover for example a review of business cycles, processing cycles, machine cycles or component cycles. The first four elements reviewed are probably from an analysis viewpoint the most fundamental in any time-given “snap shot”. Not only does this diagram show the four key institutional pillars (organization, business process, data, technology), but the arrowed lines indicating the connectedness of the areas is vitally key. For example, who (organization) owns what (data), or more in particular to the topics here, who own what components of the total agency linearly referenced data and what businesses processes are they supporting? It is suggested by building up an organizational blueprint or architectural understanding based on the Zachman framework it is more likely that a successful IT project can be completed.

The Zachman Framework is further summarized in simple tabular top-level form below in Table 57.

Table 57 The Zachman Framework

Adapted from; Innom, 1997

<table>
<thead>
<tr>
<th>Scope</th>
<th>Function</th>
<th>Network</th>
<th>People</th>
<th>Time</th>
<th>Motivation</th>
</tr>
</thead>
<tbody>
<tr>
<td>Enterprise Model (Owner)</td>
<td>WHAT</td>
<td>HOW</td>
<td>WHERE</td>
<td>WHO</td>
<td>WHEN</td>
</tr>
<tr>
<td>System Model (Designer)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Technology Model (Builder)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Detailed Representation (Contractor)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

The Zachman framework either directly or though extensions provided by various others authors (see for example, Beedle, 1996, and Sharp, 1999) provides an outline approach in terms of task (e.g, analyses or lists to prepare, deliverables, etc) for the specifics of each column, row and box. For example, in Figure 72, the “What” or Data column (from Table 57), is specified as example in more detail, utilizing work that was done for Texas DOT.

It is proposed that by the process of filing the cells of the Zachman matrix, information systems automatically become aligned with management’s corporate goals. Fuller specification of the Zachman framework are provided in Table 58 and in
The fact that LRS is integral to many DOT information systems indicates that as a wider corporate utility it needs to be best implemented within a Zachman type framework if wider institutional and organizational issues are to be addressed. Other broadly similar frameworks have been proposed by Hendrix (1998).

These particular issues are not further individually addressed here, but reflect many of the concerns underlined for GIS implementation in the work of Azad (1998).

The Zachman framework is in short really a ‘thinking tool’ to help understand complex ITIS-IT related issues, like the introduction of new LRS concepts and methods. It is suggested that it helps in organizing development thoughts and helps in developing strategies for creating flexible and agile enterprises.
Table 58 Zachman Framework: Detailed View

<table>
<thead>
<tr>
<th></th>
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<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>SCOPE (Planner) Contextual</td>
<td>List of Things</td>
<td>List of Processes</td>
<td>List of Locations</td>
<td>List of Organizations</td>
<td>List of Events</td>
<td>List of Objectives</td>
</tr>
<tr>
<td>SYSTEM MODEL (Designer) Logical</td>
<td>Logical Data Model</td>
<td>System Process Model</td>
<td>System Network Model</td>
<td>Human Interface Architecture</td>
<td>System Event Diagram</td>
<td>Business Rule Model</td>
</tr>
<tr>
<td>TECHNOLOGY MODEL (Builder) Physical</td>
<td>Physical Data Model</td>
<td>Application Structure Chart</td>
<td>Network Technology Model</td>
<td>Presentation Technology Architecture</td>
<td>Technology Event Diagram</td>
<td>Technology Rule Design Model</td>
</tr>
<tr>
<td>COMPONENTS (Sub-contractor) Out-of-Context</td>
<td>Data Components</td>
<td>Program Components</td>
<td>Network Components</td>
<td>Interface Components</td>
<td>Component Dynamics</td>
<td>Rule Specifications</td>
</tr>
<tr>
<td>FUNCTIONING SYSTEM (User)</td>
<td>Data</td>
<td>Function</td>
<td>Network</td>
<td>People</td>
<td>Time</td>
<td>Motivation</td>
</tr>
</tbody>
</table>
**Figure 73  Zachman Framework: More detailed View**

**ENTERPRISE ARCHITECTURE - A FRAMEWORK™**

<table>
<thead>
<tr>
<th>SCOPE (CONTEXTUAL)</th>
<th>DATA</th>
<th>FUNCTION</th>
<th>NETWORK</th>
<th>PEOPLE</th>
<th>TIME</th>
<th>MOTIVATION</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Planner</strong></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
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</tr>
<tr>
<td>ENTERPRISE MODEL (CONCEPTUAL)</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
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<tr>
<td>Owner</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
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<td><img src="image" alt="Diagram" /></td>
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<tr>
<td>SYSTEM MODEL (LOGICAL)</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
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<tr>
<td>Designer</td>
<td><img src="image" alt="Diagram" /></td>
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<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td>TECHNOLOGY MODEL (PHYSICAL)</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
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<tr>
<td>Builder</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
</tr>
<tr>
<td>DETAILED REPRESENTATIONS (QUIT OF CONTEXT)</td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
<td><img src="image" alt="Diagram" /></td>
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<tr>
<td>Sub. Converse</td>
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</tbody>
</table>

John A. Zachman, Zachman International (810) 231-0531
9.2.4 Improved Agency Methods II: UML

The Unified modeling Language (UML) was earlier described in Chapter 3, section 3.6.6. A list was provided in that section of the nine different types of diagram that may be undertaken with UML. These included “Activity Diagrams”, “Collaboration Diagrams”, “Sequence Diagrams”, “deployment Diagrams”, etc. UML aims to be a general-purpose modeling or diagramming language that can be other used for data or software modeling -- as well as a number of other wider deployment and organizational tasks. Thus by facilitating an environment or language for designing and making clear a wider set of activities associated with IT (and resultant institutional change) there is a wider aim of facilitating “enterprise modeling” or “corporate computing” (Taylor, 1990).

The notion is in short that the use of common OO tools can to some degree facilitate wider organizational understanding – and thus potentially acceptance. This may be key for areas such as LRS which impact many aspects of DOT operations and traditionally changes to practices have had to be clearly enunciated and sold to diverse work groups. This aspect is not further explored here, but is intended to be one of the major benefits of the wide ruse of OO approaches and UML.

9.3 National Institutional Considerations

Chapter 8 provided a review of the various road network models. It was noted there that it appeared difficult at the present time for any one (functional) national organization or agency to have a truly wider cross-cutting view of LRS that was above any one individual institutional need. Thus, for example the ITS community was producing the ITS Datum, state DOT’s were potentially to use the NHCRP framework, and MPO’s potentially the use the BTS Road Datum model. Clearly, there was both institutional and technical overlap here. Chapter 8 briefly indicated that the process of “chunking up” the national highway network seemed to potentially be duplicitous and not have benefited from consideration of what elements were or potentially could be in common between the initiatives. The NHCRP project has at least attempted to take a wider institutional role and is reviewed in a little more detail below from an institutional perspective. It is thus given some additional consideration in terms of national institutional considerations.

9.3.1 NHCRP Institutional Role

The NHCRP 20-27 project (Vonderohe, 1998) employed a wide EP of national representatives who came from a range of public organizations, software vendors and other practitioners with strong LRS experience. Some Canadian input was gained to this process. Much of the critical interaction occurred over a three-day panel meeting attended by nearly 40 (multi-state, multi-agency, multi-practitioner) participants in Milwaukee in 1994. Most who attended felt that it was a fairly unique meeting, with a variety of disciplinary perspectives and functional needs represented. The meeting was felt to gain in some large measure a practical synthesis, in particular between the core groups of field practitioners and software providers.

There was however in detail conflicting concerns of those involved principally with:
1. **Maps: Cartographic accuracy and display.** Cartographic representation is concerned with a set of lines that can be mapped to a linear datum. It provides coordinate references and linkages to extended topological, vector based GIS data models. (In reality, larger state DOTs have in fact pieced together many core maps that have used several datums on one map, e.g., Florida DOT). Display issues may be concerned with the fact that the base network which is used for LRS data management purposes may have on it "pulled lines" – lines moved to ease end user visual interpretation.

2. **Data Management: Database representational issues and data management.** Key issues here may be data normalization, or reducing data redundancy, and the choice of relational versus object database design and storage technology, etc.

New foundational ideas were developed and adopted to draw together these types of divergent concerns. The development of "anchor point" and "anchor section" are key, but not the only, examples of this. (These terms are defined earlier in this Chapter 3 and considered further in Chapter 5). The required (rather than the optional) adoption of these and other constructs while creating a solution for many also created some issues for certain field practitioners. Besides creating "a model", which could then be modified to best meet local circumstances, the 20-27/2 work drew together much important experience in LRS methods and field practices. The 20-27/2 work is being developed and extended by others in ongoing work, as well as by practical implementation at state DOTs.

Of course, not every US State DOT immediately modified its current LRS methods and plans following the publication of the NHCRP report. DOTs generally move slowly and cautiously. LRS matters in application detail are generally understood by relatively only a few people in each DOT. Sometimes the most knowledgeable person on a particular DOT’s systems may not even be a DOT employee (possibly the case for example in Maine and Vermont). Also, vendors have also been somewhat slow to prioritize implementing the 20-27/2 framework. (Some would say they currently have the elements of it, but one would dispute this. Anchor points and anchor sections can in theory be implemented in GIS, but generally with difficulty and are not vendor "supported data structures"). In addition, while there have been published 20-27/2 informational reports and presentations, there has been a failure to provide training and adequate elbow support in 20-27/2 basic concepts and appropriate implementation.

It is likely however that in the longer term the NHCRP 20-27/2 (and follow-on works) will gain at least some further institutional prominence with transportation agencies. The reasons summarized here indicate why:

1. **Longer-Term Trend In Motion:** Several transportation agencies have already essentially adopted the 20-27/2 model as the way they will develop future LRSs or will likely develop LRS (e.g., state DOT’s in Texas, Minnesota, and potentially, Utah, etc.). Iowa is an example of a DOT that is about to undergo a detailed study, at some reasonable level of investment. It has made its leaning toward the NHCRP model clear. Of course, any stated plans are always open to further review refinement.
Many other states that have considered moves this way have been restrained by lack of staff and a need to focus on Y2K problems. However, from input gained at the 1999 and 2000 AASHTO GIS-T Symposium, it is likely that further states will formally announce plans to do adopt NHCRP 20-27/2 or some follow-on variant of it (modified to reflect local circumstances).

2. Vendor Priorities And Developments: GIS and database vendors have not to date formally release complete, off-the-shelf software solutions to the 20-27/2 model. Some may argue that they have in place large components of the NHCRP model, but clearly they do not directly, at least at the current time. However, it is understood that there is a continued recognition by them of the basic NHCRP 20-27/2 work. There are at least behind the scenes some plans to further enhance current capabilities to better support NHCRP with some vendors. Some of these plans have been to date been held back not because it was not seen as desirable to do so, but because of other software development priorities (again, for example, Y2K compliance).

3. Further National Development And Support: The current, next phase of the NHCRP project, NHCRP 20-27/3 Project ("Functional Specifications for Multimodal, Multidimensional Transportation Location Referencing Systems") is continuing this work. As noted in Chapter 8, section 5, a new, somewhat more focused, Technical Panel of national experts was established to support this work. The Panel gave further credence to the technical work that had been completed before (while recognizing that there would also be some with technical reservations on particular points). The purpose of the Panel was to extend the model (for example, for temporal and multimodal aspects). It was however reinforced that perhaps there had been relatively little or no resource been provided in fully explaining the workings and benefits of the existing 20-27(2) model to a wider range of transportation agency staff.

4. Training Support: Largely out of stimulus gained from the above Panel meeting, a new one-day LRS/road data model training workshop was organized. As noted, the first of these was held at the AASHTO GIS-T Symposium on March 28, 1999. A key thrust of this workshop was intended to validate and fully explain the NHCRP model and other LRS models, and the thoughts and concepts embodied in them.

The workshop held between the different national model experts was intended as a major first step to gain a national institutional basis for a common LRS framework. However, at the current time it seems unlikely that the political climate seems engendered to support such initiatives. The current TEAC 21 legislation has focused on a move away from national standards setting and assistance and a move towards supporting more localized efforts.
9.3.2 Managing Technology Transfer

Improved methods of undertaking LRS are an example of new technology that needs to be "transferred" to field operations. A recent National Research Council report (Research and Technology Coordinating Committee, 1999) reviewed FHWA's role in technology transfer. This report was completed as the major reorganization of FHWA towards regional offices was being put into place. This reorganization effected a major disbursement of responsibilities to a local level and left a gap in the ability to espouse better practices on matters such as LRS from a national standpoint. The major recommendations of this report were:

1. FHWA should assign agency-wide management responsibility for technology transfer to one of its headquarters offices. That office should then prepare a management plan for future FHWA technology transfer activities.
2. FHWA technology transfer management plan should include a strategy for the agency's technology transfer activities. (FHWA currently does not have this).
3. Finally, FHWA needs to develop strong partnerships with those who use and implement highway technologies, as well as the decision-makers who are responsible for funding related to innovation.

9.4 Chapter Summary and Conclusions

9.4.1 Progress Achieved

This chapter has briefly reviewed institutional issues that potentially relate to LRS. It was noted that while there was no prior work specifically on LRS institutional issues, work in directly relatable areas (that is, GIS, ITS and IT adoption) seemed to provide some key and highly relevant guidelines.

A number of observations were made from these review which are summarized below.

9.4.2 Ten Main Observations

These are summarized as follows:

1. **Need for Toolkit Approaches**: No one LRS technical or institutional solution is likely to fit all circumstances. Approaches will need adaptation to local circumstances.

2. **LRS and GIS Efforts**: LRS efforts should be closely institutionally associated with GIS efforts of which they are technically intrinsically part. There may be occasions where for particular or special reasons where this may not be so, and then LRS should be pursued "independently but communicating".

3. **Top Institutional Concerns**: It has been found with GIS that, a) top management support, and b) location of the responsibility in the agency are key institutional concerns.
4. **Top Management Support:** Top management support and understanding for LRS efforts needs to be gained. It may be a fairly dry topic for many DOT top management, who may be pressed by daily operational decisions. However, the absolutely key role LRS can play in integrating and providing access to the agency's significant legacy and ongoing data investment needs to be made clear.

5. **Organizational Location:** The four case studies reviewed in this document indicate there are a variety of organizational locations that can work but careful consideration needs to be given to these.

6. **Institutional-Technical Development Frameworks:** The literature indicates that enterprise technology frameworks that include institutional and organizational issues are likely to be more successful than frameworks that are only focused on technical aspects.

7. **Zachman Framework:** This framework is one example of an IT framework that be useful for an enterprise support information system such as LRS. A case study use of the Zachman framework with LRS needs to be made.

8. **Funding:** While not focused on explicitly in this chapter, adequate funding of the enterprise-level LRS initiative is key.

9. **National level Role:** There is currently an institutional schism between the alternative road data approaches at the national level. It would seem that despite some preliminary efforts (such as carried out in connection with thesis) to reconcile these disparate road data efforts, these are kept apart by institutionally set and distinct institutional forces. The road data model efforts as things currently stand are therefore likely not to be further integrated. This higher-level institutional issue leaves a particular issue for local transportation agencies who are likely to be faced with competing and alternative road data model and LRS demands.

10. **Further Research:** This could further identify and focus on successful LRS implementation from an institutional perspective. The nature, form and remedies for institutional issues likely to associated with LRS implementation and support would be more closely traced out. This would include gaining adequate institutional support and necessary agency actions for training and education.

### 9.4.3 Main Conclusions

The integration of spatial data within and between transportation agencies is increasingly important for gaining the greatest value from an agency's information resources. The successful implementation of an enterprise LRS may largely be attributed to institutional organization and support. Designation of responsibility for managing and maintaining LRS and GIS operations to specific offices was a common theme between the case studies. Effective management of an enterprise LRS requires clear assignment of responsibility for coordinating and maintaining the system.
LRS projects, like GIS projects, have often failed to meet the basic criteria of good "project managernship". Such projects have gone rampantly over-budget, failed to maintain sponsor/management support and not meet specified goals and project targets. Clearly, like any other IS project, public domain LRS projects need to be utilize "best practice" project management techniques, such as promulgated by the Project Management Institute (PMI). Such techniques can involve the appropriate and skilled technical standard tools (such as GANNT charts). They may also utilize other institutionally-focused techniques that are geared to maintain and manage user and top-management interest and support through projects that may be multi-year, institutional turf battles, etc. These techniques may draw from an arsenal of tools and techniques which sound obvious, but are often poorly understood or perceived by technologists. They may include for example, the use of facilitators, the use of “Groupware” in system design, appropriate JAD (Joint Application Development) and RAD (Rapid Application Development) techniques, Change Management procedures, and regular wider community project news mailings, briefings, etc. Such is the absolute importance of this topic, the author will be running a one-day workshop on Project Management techniques for GIS-T at the next AASHTO GIS-t Symposium.

Clearly, further research work is required on LRS institutional issues at both the local levels and national levels. In the current political climate, where the federal role focuses on safety, it is unlikely this will be federally supported top-down. The next chapter picks up on the need to design flexible technical approaches, in one part, to meet diverse and potentially changing institutional needs.
9.5 Chapter References


10 Final Conclusions and Summary

Make level paths for your feet
And only take paths that are firm
Do not swerve to the right or left
Keep your foot from evil
Proverbs 4 v26

10.1 Chapter Purpose

Linear referencing started with mankind's earliest activities chapter (see Chapter/section 1.2). Guidance on and marking off of progress on the hunting or fishing path or trail itself would have been achieved by existing landmarks or placed markers that kept one, "from swerving to right or left" (in the terms of the quote above). The Romans were the masters of the "level, straight, and firm paths". In the centuries since, highways first became more crooked and then, in the later half of the twentieth century, also more complex. Linear schemes in recent years thus need to be adapted to trace paths through more complex highway forms. However, little adaptation of the basic scheme (linear reference methods) has gone since Roman times.

With this background, this thesis has had five summary aims:

1. Foundation Research: The research attempted to create a research foundation for an "under-considered" area of spatial research, that is, of the one-dimensional spatial location reference case.
2. Methods for "Messy Problems": Endeavor was made to create and test a basic research methodology for research into "spatial messy" problems (which LRS is one example of).
3. LRS Practitioner Guide: Provide modern-day practitioners of more linear referencing with the guidance they need to accomplish their work in a rapidly changing technical environment.
4. Reflective Thinking: Provide one example of "reflective thinking" in the area of "messy" problems.
5. Foundational Research: Provide a basis for further research in an area that may regarded in a formal sense as a new area.

In this thesis the overall approach taken has been to combine:

1. Theory and the context of general principles
2. The direct field experience and current practice (as outlined in Chapter 2).

The field experience appropriate for practitioner-focused research was principally gained through four case studies, and two expert panels. The organization of the thesis, generally by research topic, rather than for example by Case Study, was also intended to provide a working framework for those who must evaluate either specific aspects of linear referencing (or, entire linear referencing systems), as well as those researching spatial "messy" problems. This final chapter
first summarizes the research approach taken. It then summarizes the ten main results and findings of the thesis, drawn from across the thesis as a whole. It then makes a number of field recommendations on LRS use. The research was rounded out by the undertaking of a basic LRS conceptual exercise on the basis of the recommendations and observations on the next section. While the details of the conceptual exercise are not included in the main body of the thesis itself, (as they were somewhat outside of the main flow of work), they are summarized in Appendix E. The exercise undertaken attempted to address a defined set of issues related to the design and use of linear referencing systems (LRS).

Further research is then identified, as a set of higher-level topics and a set of more focused technical topics. A set of final conclusions are drawn, including on progress achieved and technical issues. A higher-level philosophical view of the current standing and status of LRS research is made. Finally, conclusions are drawn on the potential contribution of the research conducted here.

The critical purpose of this chapter is not to repeat what said in earlier chapters (and summarized at the end of each chapter), but to draw important cross-area synthesis. The synthesis and resultant recommendations draw heavily on the body of the thesis. While specific back references are given at may key points, in other areas the relevant chapter is fairly clear, or, the references if provided would be to many locations.

10.2 Brief Review of Research Approach

The research approach undertaken here was intended to facilitate LRS activities by providing:

1. An overall field basis and framework, and
2. A general model for conducting such practitioner-focused research.

As described in Chapter 2, a practitioner-focused research methodology was employed, drawing on the work on research methodologies in parallel fields (in part, because relatively little example was found for planning information systems). This approach involved a five-step research methodology that was, in summary:

1. **In Depth Literature Review**: This included the added dimension of reviewing the immediately parallel fields (as for example identified in Chapter/section 3.5).

2. **Focused field Case Studies**: The added focus here was to ensure initial sufficient field knowledge that the conduct of survey and the instruments could be fully effective. While case studies often provide the backbone of practitioner focused research, they typically "do not tell the whole story". Thus, additional sources of input are required.

3. **Use of Expert Panels (EP)**: As proved here, the EP were exceptionally useful in adding to, "fleshing out" and reinforcing information gained in the case studies. The EP also covered topics that it was not appropriate to cover in the Case Studies in any depth (e.g., the road data models). In many practitioner areas, field "experts" often contain unique reservoirs of knowledge that may not be well recognized in the formal literature (as was here the case).
4. **In-depth Study of Focus Topics:** These are undertaken on areas that require particular examination. An area where such treatment was given here is that of Time, which was drawn out and treated separately in material drawn from the literature reviews, case studies, and expert panels (as per Chapter 7).

5. **Undertaking a Reflective Practitioner Exercise on the Work:** This involved a detailed examination of the results of the above studies, and a matching with wider field experience. (In broad-based practitioner-related research, it may not be possible know, even within broad bands, what exactly may be found in the earlier part of the research exercises. Thus, it may not be possible to equally focus on all the interim research results gained. It may be necessary or appropriate to select particular areas for focus in later parts of the exercise. This was to some extent true here, even if the recommendations attempt to cover the whole gambit of the research).

Such research approaches need to be applied with careful development, energy and dexterity for success.

Through the above five-step research step methodology, nine co-related tracks of research were put in place for this thesis in attempt to provide a research foundation for the LRS field (see, Table 8, in Chapter 2, and Table 59, in this chapter). The Case Studies played a unique role in grounding this research "in the field" (which is where such research ultimately belongs with a 'practitioner' topic). Chapter 6 with the supporting material provided in Appendices E and F summarized the findings of the LRS Case Studies. In that chapter, a number of detailed recommendations were identified for the preferred field coding and use of LRS (see Chapter/section 6.13). Additional research work carried out in this thesis, involved the two Expert Panels, which focused on a more detailed examination of the existing road data models and on intermodal and temporal aspects. Detailed field recommendations are further summarized and reviewed in this current chapter’s sections.

### 10.3 Research Track Summary

It was noted in the introduction to Chapter 3 that there has been little “contextual” consideration of LRS. In this light, it is hoped that the results here may make some wider contribution. This section provides a review of some of the key findings of the thesis. This section draws together some of the ten key findings that are listed at the end of each chapter.

At the highest level of observation, it was noted:

1. **Need for LRS:** Analysis of the transportation system and development of efficient management and maintenance systems requires the integration of diverse data about the transportation network. As noted by Vonderohe et al. (1997), “the greatest incentive for policy concerning LRS is cost savings realized from data integration, data sharing and the reduction of chaos.”

2. **Tackling the Institutional “Island Problem”:** Different divisions within a transportation agency typically manage different sets of transportation data. The
Table 59 Research Track Findings

<table>
<thead>
<tr>
<th>TRK</th>
<th>RES - ULT</th>
<th>Field Overview</th>
<th>Epistemology</th>
<th>Semantics</th>
<th>Technology</th>
<th>Current Road Model Research</th>
<th>LRS case Studies</th>
<th>Modal Expert Panel</th>
<th>Model Expert Panel</th>
<th>Institutional Issues</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Greater role in transportation agencies in managing data</td>
<td>Different terms and concepts used by different disciplines</td>
<td>Different terms used even within LRS field</td>
<td>Claim that GPS will do away with LRS</td>
<td>Existing research largely “model-in”</td>
<td>LRS (road and network definition) full of “field pathologies”</td>
<td>Time important factor; Allow navigate, cruise, etc. Difficult to model.</td>
<td>Models constructed to meet different needs</td>
<td>No one LRS model fit all needs</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>Importance of managing linear data growing</td>
<td>Significant historical lineage of geographic and spatial modeling to tie into</td>
<td>Route a key concept – understood many different ways</td>
<td>Larger amounts of traversal-based data being collected (e.g. data vans)</td>
<td>Epistemology of field to be set – many conflicting terms; “whose research field is it?”</td>
<td>Agencies wish to code up networks in different ways</td>
<td>Need to allow modal network flexibility</td>
<td>Tie to data maintenance issues</td>
<td>Within agency issues – different local information sub communities</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Little or no prior LRS academic research (other than that on data models); see BTS CD-Rom</td>
<td>Flexibility required in approaches – different and valid views of LRS and user requirements</td>
<td>Hierarchy of network elements; defined differently by alternative transportation sub-communities</td>
<td>GIS -spatial more accessible &amp; demands for spatial analysis</td>
<td>Models need integrating</td>
<td>Particular flexibility required for routes and inter-sections</td>
<td>20-27/2 model main contribution: real world to map coordinates</td>
<td>Progress, but need further work to integrate languages and needs of different modes</td>
<td>National problems of LRS data integration. As above any one sate, need a national sponsor to help propose solution?</td>
<td></td>
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integration of these diverse databases is generally accomplished through the locations of features and characteristics along the transportation network.

These research tracks and three of the main results of the research by track are briefly summarized in Table 59. The table includes in summary from the three main findings from each of the thesis research tracks.

This table is the complement of Table 8 (at the beginning of the thesis in Chapter 2, Research Methodology) that defined the original research tasks and goals.

10.4 Existing LRS Practises: Ten Synthesis Observations with Recommendations

Any recommendations for “best practice” in LRS must be made relative to the goals of a robust system for the management of transportation agency data (as reviewed in Chapter/section 3.5.8). Particularly relevant are the goals for applying LRS to the implementation of GIS-T, because these typically represent the most effective off-the-shelf solutions (Chapter/section 3.5.9.1). This research through the case studies has determined a set of more specific key goals of a robust LRS supporting GIS-T.

This thesis has covered a number of topics pertinent to a fuller consideration of LRS. The Conclusions section of each chapter contains a set of eleven specific key observations of the topics covered in the particular chapter (i.e., ninety in all up to this chapter). They are collated together for the thesis as a whole in Appendix H. As stated, it is not the main intent of this Conclusions chapter to repeat or reconsider all of those detailed topic observations, but to draw still higher cross-area synthesis on key findings.

This section also provides a set of observations on what a preferred best practices technical framework for LRS should reflect or contain. The emphasis of this section is really within the frame of current LRS practices, placing these within the appropriate context, and then adding or amending to these.

The following are a summary of ten main observations ‘reflections’ on LRS gained from across the research work carried out for this thesis. The ten selected summary topics (with an additional summary one) are:

1. LRS Importance and Role to Transportation
2. Spatial Data Collection: GPS
3. Linear Reference Methods
4. Data Storage: LRS
5. Existing Road Data Models
6. NHCRP 20-27 Model
7. Spatial Representation
8. Time
9. Maintenance
10. Institutional Factors

Summary: Diversity, Flexibility and Toolkit.

The topics represent a wider critique of how LRS is done to day and some possible directions for improved business practices. It is hoped that that the synthesis of working conclusions drawn
below are a major practical working contribution to the field and provide some higher level critique on the LRS field.

10.4.1 LRS Importance and Role to Transportation:

Judging from the DOT experience reviewed in this thesis, LRS at the present time is becoming increasingly practically important (rather than less so, as was previously supposed by some). This is due in large part to increasing amounts of transportation network data being collected. The use of GPS-equipped automated data collection vans in particular have increased the practical importance of LRS. It was briefly explained in Chapter/section 4.5.1 that data generated by automated highway data collection vans is typically reduced immediately to traversal-based measures. However, difficulties of institutionally adopting use of a common LRS (as well as agency level GPS procedures) are still today currently critically restricting integration of DOT core business system data and system interoperability.

It was seen through the Case Studies LRS that LRS often is used to maintain what may be regarded as, “engineering level data” (e.g., highway condition, potholes, etc.). However, it is tool principally used for highway planning purposes or the management of highway networks (see Chapter/section 3.5.8). Given this practical user focus of LRS, while a concern with geometric accuracy has some relevance in an engineering environment, the greater part and use of LRS in most DOT’s does not necessitate the highly accurate management or display of data. For analysis purposes, it may be sufficient for many use areas to know the (relative) location within say 5 or 10 meters. LRS can display towards this level of precision with 1:24,000 scale maps.

For base map and display purposes, many DOT’s still use 1:24,000 (or, even 1:100,000) base maps and many highway features may be simplified or reduced to simpler line forms. As more accurate data becomes available through GPS assisted technologies, so they will be a need to appropriately store and display it. There will always be needs to reconcile LRS data to more accurate data sources. However, arguably this issue has got relatively emphasized attention, when in fact the main practical uses of LRS to the present date have been more restricted (“humbler”) analyses at a “planning level”. The ability to relate to more accurate coordinate data for example, may be highly useful for some engineering-level applications. However, many applications, such as the ISTEA management systems (e.g., bridge, pavement, congestion management, transit, safety and intermodal) may not require their operation on highly detailed base maps (or, have the data to support or need it).

In short, LRS activities should have strong view to engineering and geometric level of accuracies, but the current main uses of LRS for “planning level” activities (where relative distances may be quite adequate) should be recognized (and separated from “engineering stationing” activities).

Recommendation: LRS should be transportation agency user-needs driven. That is, LRS should be set-up in a transportation agency in a manner and form where transportation user needs requirements indicate most benefit. Experience to date has indicated that this is generally within a planning-level context, in particular for use in management information systems. This observation has direct implications for example for:

1. LRS Focus: That is, the nature and goal of activities undertaken, which typically includes a focus on DOT management application systems, often run by a Planning Section or similar.
2. **Data Scale and Accuracy:** This may typically be at 1:24,000 scale in modern day usage terms.

3. **Types of Analysis Undertaken:** These are quite typically annual, state system level maps.

### 10.4.2 Data Collection: GPS:

GPS use (as reviewed in Chapter/section 4.5.1) is bringing a significant technological and business practice change to the transportation data field. It has meant that spatial data (including that associated with linear features) is gathered much more quickly and effectively than before.

A significant potential justification for the use of LRS is the increased use of automated data collection techniques, including the GPS-equipped vans. The vast bulk of DOT data today (looking purely in data volume size terms) is collected by GPS-enabled automated data collection vans (that is, in DOTS where such vans are used, which includes all of the New England states, for example). These vans may be equipped with many automated data collection devices such as to collect videolog data, roll and pitch, highway condition, including pavement cracking, etc. The vans are in some estimates in effect doubling in volume every 3 to 4 years the total amount of data held in a DOT. Essentially the data collected from these vans while at an individual point level may be considered “GPS based” is immediately reduced to office use and are “traversal-based”.

All data points will be available as originally recorded with a 3 (or 4) D location key. Most DOTs spend several million dollars a year on the collection of linearly based traversal data, including through the use of GPS-equipped videolog vans. For example, Connecticut DOT spends several hundred thousand dollars a year on its highway videolog program.

This has meant that increasing amounts of ‘traversal-based’ data are being collected (as reviewed and briefly justified in Chapter/section 4.5.1). This at a general level provides an overall wider justification for the increased working interest in LRS (and its optimal set-up) and in providing improved frameworks for constructing and operating it. In particular, it also creates a need to keep multiple sets of geometries stored for one highway entity, as for example the same road or section of road may be potentially surveyed several times a year.

Of course, GPS highway data collection need not be reduced to LRS format. However, it is often provides facility to do so to support many DOT highway applications.

While arguably the problem of data in previous years was a lack of accurate data in DOTs, it has been sometimes said that GPS has in fact meant a problem of “data overload”. Many DOTs have collected significant amounts of data without it apparently being put to any clear use. Data only becomes “information” when contextually analyzed in the presence of other data and becomes “knowledge” when information is further analyzed in the context of further contextual (including historical) information. “Data overload” can thus add to lack of the best available information and knowledge” being given to DOT management. **LRS is one key technical tool or method in facilitating DOT data reduction.**

As reviewed in Chapter/section 4.5.1, the technical use of GPS for measurement is well understood. However, DOT’s have also not learnt yet to deal with the “bridge over the river problem” (that is, the difficulty of maintaining spatial congruence and integrity between data sets that are maintained by different application areas, groups or departments). Learning to deal with
these issues requires learning to institutionally deal with the use of GPS. This topic has been little addressed to date. An institutional set of procedures for dealing with GPS has itself to be part of a wider and integrated institutional set of procedures for collecting, managing, disseminating and updating agency spatial data. The NHCRP has posited this as a topic for potential research. As with the topic of this thesis, this topic will require drawing together a range of technical concerns with a range of DOT user and operational uses and needs.

A following section briefly further reviews LRS and linear data maintenance issues in a little more depth (see Chapter/section 10.4.11).

**Recommendation:**

1. **Technical:** As many GPS traversals may now be collected for a highway, highway data objects and the LRS schema should be able to store or access multiple sets of geometries.
2. **Institutional:** DOT's need to put in place agency level procedures to handle the use of GPS and GPS-collected data. This would encompass many detailed activities for which GPS equipment is now used, and would include all GPS-based traversal based data.

### 10.4.3 Comparison of Linear Reference Methods

While a thorough analysis of all the pros and cons of different LRM s is beyond the scope of this document, some general comments are offered to highlight the potential strengths and pitfalls of the various LRM s. Different methods will always be required to meet individual needs; however, the characteristics of each must be considered prior to implementation.

Three general linear referencing methods were described in Chapter/section 4.2.2:

1. Named route/milepoint
2. Control section
3. Link-node.

Built upon these fundamental LRM s, many variations in the application of linear referencing are possible, as evidenced in the case studies. Ten of the key selection criteria or issues to consider and compare when designing or refining a linear LRS include:

1. Efficiency in the number of linear referencing control elements (e.g., number of traversals, number of control points, etc.) – this may impact both performance and maintenance costs
2. Stability and maintainability with respect to geometry update
3. Stability and maintainability with respect to attribute update
4. Storage efficiency for event (attribute) data
5. Ease of coordination with separately managed, linearly referenced databases
6. Availability of robust, off-the-shelf supporting software tools
7. Ease of transition from the current data organization and environment
8. Reliance on field sign infrastructure and associated maintenance costs

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9. Compatibility with current work organization (e.g., preserving the relationship with current highway maintenance jurisdiction boundaries as well as existing methods).

10. Existing available COTs to implement the

**Recommendation:** In short, any LRM can be used and made to reasonably work. In selecting or setting up a particular LRM, the about ten selection criteria should be borne in mind and weighted accordingly.

### 10.4.4 Data Storage: LRS

As was noted above, Chapter/Section 4.5.1 reviewed the use of GPS and LRS.

In an imperfectly understood world, is it important to know, absolute location (i.e., \(x,y,z,t\)), or, relative location \(d\), with respect to a known local point? There may be no universal “best choice”. It should of course be understood that all spatial data:

1. Even “absolute data”, is to some degree *relative* (e.g., data appears within some projection system, or, because measurement error is involved, etc.).
2. Relative data has some degree of absoluteness about it (e.g., it is a fixed distance from some landmark).

Despite the undoubted advantage of GPS for original field *data collection*, for the transportation data management and analysis community, LRS for data storage has a number of intrinsic practical advantages. These advantages pertain at least at the present time. The three key advantages are in short:

1. **Legacy:** The tie to existing DOT legacy historical data sets (which typically are in some LRS format).
2. **Reduction of Data Redundancy:** This was briefly reviewed in Chapter/section 4.4 comparing static and dynamic segmentation. There is a reduction of data redundancy, where for example the condition does not change between linear data recording point \(x\) and linear data recording point \(y\), but all the intermediate data recording points do not have to be stored. The distance between \(x\) and \(y\) can be significant (even hundreds of miles in some cases) and represent thousands of (similar or identical) consecutive readings.
3. **Route Association:** The use of LRS allows data to be automatically directly associated in the field with the transportation network spatial feature with which it is associated (i.e., the route, roadway or traversal). The issue of having to snap points to feature (that is itself intrinsically prone with issue and potential field or office error) is automatically done away with.

A number of technology and technical developments of potential use in considering LRS, including for data storage, were proposed in Chapter 3 (Chapter/section 3.6) and in Chapter 4. Chapter/section 3.6.5 (and Appendix G) briefly reviewed the use of OO approaches. It would appear they have strong potential for improved model frameworks for LRS. As reviewed there,
OO approaches appear in particular to offer improved end-user flexibility and ease of use. All paradigms have a cost, and one of the costs for OO is the set-up and support or more complex data structures. The other historic disadvantages of OO (e.g., in short, performance, transition from other paradigms, and propagation of design errors) need to carefully evaluated in design and test systems. However, such considerations may increasingly be overcome with:

1. Advances in OO methodology and technology
2. If the costs of the OO exercise are spread among a wider DOT community.

Once such a system is fully setup and tuned by professional application developers (perhaps not by individual DOT internal bespoke programming), much of this should be hidden from the end-user. DOT staff should gain from the use of more “intelligent” highway entities (i.e., “self-organizing” and “self-managing” objects), that may help address some of the error prone characteristics of current manual network coding and checking methods. Capturing the network data logic and cleaning methods may be a key part of the OO design exercise and an overall end benefit of the approach.

**Recommendation:** A LRS should enable:

1. **Data integration:** An LRS must enable the integration of transportation data through the locations of features, characteristics and events that occur along the transportation network. This includes through the variety of “cases” reviewed in Chapter 6 of this thesis.

2. **Interoperability of transportation data systems:** Moving a step beyond “as-needed” data integration, a robust LRS should enable separate information systems to truly interoperate as integrated transportation information systems (ITIS). For example, a pavement management system might have on-demand access to traffic volumes from a separate data system. This is typically achieved within an ITIS by referencing all data locations to a single linear datum, enabling systems to interoperate without requiring on-the-fly translations between LRM.s.

3. **Implementation in GIS:** The implementation of LRS in GIS is the heart of a GIS-T. The union of LRS with GIS potentially enables translation between linear locations (i.e., traversal, offset) and geographic locations (i.e., x, y), thus providing the ability to directly display linearly referenced data by dynamic segmentation. The GIS centerlines may be coded in GIS-T by both the linear and geographic measures. This may become the means for translating between the two referencing methods. This is essential for enabling this integration between LRS and locations collected by GPS.

Some linear referencing methods cannot be readily implemented in commercial-off-the-shelf (COTS) GIS software. Given the importance of GIS to modern transportation applications, the capabilities of GIS COTS software should be taken into consideration when designing a robust LRS.
4. **Use of OO Approaches:** While other approaches may be used, it would appear that a “toolbox approach” when fully set-up in an OO framework offers the greatest potential net advantages for implementing LRS. An evaluation exercise needs to be completed on a basis where the limitations and costs of OO are recognized. The design of the tools, and costs and benefits, ideally need to be associated with the wider transportation community or at least a wider section of it (such as state DOTs).

10.4.5 **Existing Road Data Models:**

There have been a number of existing attempts to create road data models (as reviewed in Chapter 5). None of the existing road data models seem to flexibly fit the needs of the wider transportation marketplace. However, they may meet the needs of individual communities of the transportation industry. These existing road data models offer somewhat “point” solutions. The models have also been produced independently from each other. (The models were reviewed and critiqued in Chapters 6 and 8).

At the present time none of the existing proposed road data models have gained universal popularity. Reasons for this in short include:

1. **Their complexity:** The models are relatively complex to understand, by most, and certainly the average DOT practitioner. Few individuals understand LRS, transportation, and data modeling (and, in particular, modeling or data diagramming languages, such as UML). This then puts the models past the ‘ready reach’ of understanding of the vast majority who work operationally in state DOT’s (as well as many other transportation practitioners).

2. **Their lack of flexibility:** The models are, “a model”, and do not permit alternative forms, at least directly or explicitly.

Two key seminal or fundamental LRS road data model technical issues include:

1. **Cartography:** In this context, it involves tying the geographic representational network to real world coordinates. This may be referred to as facilitating cartographic representation. The use of anchor point and anchor sections facilitates the use of different cartographic projections and techniques (e.g., “pulling lines”, for reasons of improved cartographic display).

2. **Database:** This involves semantically representing the geographic network (in particular the variety of network forms that occur). This may be considered as facilitating database representation, as it would provide forms to more readily map real-world spatial regular cases, special cases, or “pathologies.

The existing road data models do not account for time.

It may be seen from the review carried out in Chapter 6, that the main difference between the models is explained by understanding the different transportation user communities they were created for. The 20-27(2) model is the most favored to date by state DOT’s and is summary reviewed in a little more detail below. The Dueker-Butler model (see Chapter/section 5.4) is intended for a wider set of transportation uses than LRS, but in any event appears to share the same logical basis as the 20-27(2) model.
Recommendation:
1. National Prompt: Further encouragement needs to be given by the wider set of transportation communities (especially individual state DOTs) to federal agencies or other national organizations to further develop and integrate the road data models.
2. Model View: It needs to be realized that at the present time, “no one model fits all needs”

10.4.6 The NHCRP 20-27 Model:

The 20-27(2) model or Vonderohe model was reviewed in a little more detail in Chapter/Section 5.2.2., and further in Chapter/section 8.6.

The NHCRP model largely focuses on the needs of highway departments. It does not offer so full a cross-modal or comprehensive transportation solution. In reviewing a one-page diagram of the 20-27(2) model, (see Figure 39 and Figure 40) the model appears to have a conceptual elegance and simplicity. In covering many of the main issues addressed in this thesis, and providing a synthesis on one page, the model does provide such a synthesis. However, it would not for example first appear that one needs to have to read a 400-page reference document to actually use the model in the field. As in particular Chapter 6 showed, “the doing is all in the details”. In comparison, the originators of GDF do provide for assistance with the use of their model, a manual of, in fact, 400-pages (and, much of that is essentially concerned with the coding, not “the art and practice”). As current projects in states such as Iowa are showing, the 20-27(2) model needs a lot of ‘additional instantiation’ to be locally useable. DOT input indicates that the 20-27(2) model needs with it an extensive manual to best make it “field useable”.

The 20-27(2) model includes within it a reasonable solution to the first foundational issue (i.e., “cartography and mapping”), or, the issue of tying to real world coordinates. The use of anchor points and anchor sections provides a reasonably simple and robust solution to tying the LRS mapping to real world coordinates. It is also a solution that has direct analogy to other fields (e.g., use of benchmarks, etc.). The model seems to have gained some current cognizance in the DOT user communities. The 20-27/2 model does not so well address the larger set of database representational issues from the point of view of the diverse needs of wider transportation information communities (as summarized in Chapter/section 10.4.1 above).

From a practitioner implementation reflection viewpoint, a quite basic, but also fundamental observation is that the 20-27/2 model is relatively simple and elegant – but, really understood by only a few in the transportation community. The major intellectual contribution of the model is not necessarily the model form (which is a fairly basic level statement of LRS concepts), but the introduction of anchor points and anchor sections, packaged with some of the accompanying technical details (as summarized below). Procedures for defining anchor nodes and sections are not well described in the NHCRP 20-27 report. Some practical recommendations have been generated in the work here.

10.4.6.1 Anchor Nodes
In setting up a LRS, it should be possible to unambiguously locate nodes in the field to within a specific distance tolerance. This may be for example, to initially within 5 metres (with the goal of attaining 2 metre accuracy of key references, such as nodes, points, other locational references, etc., as soon as possible).

For most simple intersections, the “intersection of roadway centerlines” would enable the node to be located within the initial 5-metre tolerance. For more complex intersections, bridges or other features with ambiguous node locations, the node should have a location description that enables locating the node to within the distance tolerance in the field. It is very important that the anchor points, or their equivalent, be consistently and systematically locatable in the field, as all linear locations will be taken relative to these points. This will become particularly important when the nodes (and links) are put to use in the field.

To enact an accuracy standard for node locations, a distance tolerance must first be selected, being the distance within which one can relocate the node in the field. A practical approach is to choose a distance tolerance that can be met for most intersection using the intersection of the centerlines (e.g., 5 metres, then 2 metres). Complex intersections or other features for which the node could not be relocated within this tolerance would require a more detailed node description. Once the LRS procedures for node creation should include establishment of node location descriptions to meet the accuracy standard.

It may also be desired to establish several distance tolerances by which node locations can be classified (e.g., 2-metre, 5-metre, 10-metre). Existing nodes could initially be classified in the ‘low accuracy’ class and moved to higher accuracy classes as they are reviewed and verified over time.

10.4.6.2 Anchor Sections:

Anchor sections are defined as existing between selected anchor nodes. Though the NCHRP model does not require them, it is often useful to establish nodes (corresponding roughly in function to anchor points) at overpasses where there is no interchange or intersection. On the other hand, it often is not desirable to create nodes at all overpasses (including over-passing ramps) for complex interchanges. The procedures for establishing nodes at overpasses and interchanges at present are not fully detailed.

An issue that has not been made clear with the use of the 20-27(2) model is how geometric change (at for example a low route/geometry unit level) is propagated though the system (e.g., link level, route level, network, etc.). While the use of anchor points and sections alone does not provide an answer, their existence may help facilitate the encoding of logic to meet these ends. While COTS software may ultimately provide possible solutions, existing business practices need to be factored in. For example, many DOT’s do an annual update of the official or log analysis network. Easier data maintenance procedures may facilitate the more frequent recognition of update data.

The overall recommendation on the NHCRP Model is:

**Recommendation:** The 20-27(2) model should be further developed. This should include the development of improved:

1. **Model Form:** Flexibility in the basic model form.
2. **Support:** Emphasis on providing field implementation and coding support, including through the use of detailed work case studies and examples. This could be summarized as a field practice manual.

3. **Anchor Points and Sections:** More precise advice along the lines of that provided above should be formalized in particular within the guidance manuals.

### 10.4.7 Spatial Representation:

As previously noted, in the previous two sections on data models, spatial representation issues include:

1. "**Semantic Representation**": This involves selecting an ontology for the field. Associated tools then need to be prepared to both represent networks and the LRS that sit on them.
2. "**Spatial (Cartographic) Representation**": This includes the issues tying to real world coordinates, and whether this is as close as possible for accuracy or altered for comprehension.

A richer set of tools are required to represent networks (for one reason, so that LRS can be most accurately and appropriately placed on top of them, but potentially also potentially to meet other transportation needs). The anchor points and anchor sections seem to offer a robust conceptual solution to the issue of tying to real world coordinates. Further work is now needed on defining in database and software engineering terms the geographic network on which LRS is placed. In particular (as denoted in Chapter/section 6.8), the extension of LRS to local roads necessitates the representation of more diverse roadway types (e.g., rotaries, cul-de-sacs, divided highways, etc.) so that LRS traversals can be more accurately and facility associated with the network.

Some particular areas of focus concern within spatial representation are:

1. Variable spatial accuracy and display
2. Network cartographic forms
3. Local roads.

#### 10.4.7.1 Variable Spatial Accuracy and Display

It was argued above (see Chapter/section 10.4.1) that strong attention has typically been given in state DOTs to relating to engineering levels of accuracy. It is an appropriate part of the engineering culture. DOTs historically been engineering organizations. It was however noted in Chapter/section 3.5.8.1, that their roles have essentially already turned to one much more focused on transportation data management. This again suggests a change in role from a narrow mathematical view of LRS activities to a broaden MIS view, with the issue not being for example "GPS versus LRS", but creating O/RDBMS environments and tools and relating to GIS.

A particularly strong focus on engineering level of spatial data accuracy has perhaps been at the relative expense of other issues of concern in the current practical and typical application use of LRS. It is true that for some applications there is a potential benefit from the display of LRS at more accurate display levels. (For example, some, but not all, accident reconstruction activities, compared to safety analyses, which may be carried out at grosser levels of map detail).
However, the converse is also true; too much detail may be unnecessary and cause visual confusion or overload in other cases.

Different parts of the road network may be available in different levels of digitized accuracy. For example in Florida, some counties have highly accurate base maps, others do not. Different applications may wish to display network data at different levels of spatial accuracy or detail. For example, a Tranplan transportation network modeling application may only require a straight-line representation between two network nodes; an accident analysis at a particular intersection may benefit from having a more accurate display of the linearly referenced data at that point.

Roads and railroads were often built along river banks. At certain scales (i.e., 1:24,000 and above) for cartographic display purposes it is desirable to “pull lines” - so that, for example, the road does appear to be running in the river. Standard COTS GIS routines need to be in place to automate these procedures. These exist now for example for the automatic placement of highway shields (so that for example north-south route shields do not interfere with east-west shields, etc.). Tools to achieve this can be set up so as to be largely automatic, one command (which may require some user fix-up) or in toolbox form that can be set-up by the user to deal with particular contexts.

Consideration of the display of lines provides an example. For many applications, operating quite suitably for their purposes on grosser level networks, a simple line connecting two nodes may be sufficient detail. The Southern California Council of Governments (SCAG) transportation network of the Los Angeles basin, has 650,000 links. On such a gross areal networks, a more detailed display is in user terms, ‘a negative’.

As noted, strong concern on engineering accuracy is a valid concern for engineering focused applications. However, within the practical limits on available research activity, this has meant that perhaps a focus on transportation community core user issues and data management needs (which it appears happen to be mainly at the planning level) has relatively suffered.

### 10.4.7.2 Network Cartographic Forms

The research conducted for this thesis (in particular, see Chapter/section 6) provided a sensitivity to the issues of coding LRS through even slightly more complex highway network forms and features. Table 1 listed the basic network linear forms. At a more detailed level, for example on intersections, many states have struggled with the issue of managing ramp level data (as reviewed in Chapter/section 4.2.5). In display terms, detailed intersections (and ramps) do not appear at 1:100,000 scale, but do usually appear at 1:24,000 scale (see Chapter/section 3.5.3).

As a response to these issues, the Case Studies gave some particular attention to “traversal cases”. While for coding purposes, these might be deemed special cases, in fact in on the ground highway reality, these “special cases” may represent fairly common highway forms. In fact, many other more truly special forms exist. The cases investigated in the Case Studies were: divided highways, ramps and approaches, non-contiguous traversals, one-way pairs, layered or tiered roadways, service roads, individual lanes, associated facilities, rotaries, cul-de-sacs and proposed roadways (as analyzed in Chapter/section 6.6).
Appendix G gives some further summary consideration to the creation, use and maintenance of such network forms, and they are further summary reviewed in the next section (Chapter/section 10.5) of this chapter.

10.4.7.3 Local Roads

Transportation agencies, as they increase their management function provided on roads, and as transportation data management “goes downstream”, are increasingly looking to place local roads into the database (See Chapter/section 6.9).

This includes both DOTs (who may in some states such as North Carolina carry out maintenance for all local roads), MPOs (such as the Delaware Valley Regional Planning authority), County highway authorities, and townships, who wish to more closely manage (or, manage, period) their highway assets.

**Recommendations:** From these considerations, a LRS ideally setup needs to have the following more specific abilities:

1. **Variable Spatial Accuracy:** The LRS system should support multiple cartographic/spatial representations.
2. **Line:** While it may be vogue to consider that more detailed spatial representation are intrinsically cartographically superior, the user needs analyses undertaken in this thesis indicate that for many transportation applications simple line representations may be wholly adequate.
3. **Cartographic Forms:** Create a framework to facilitate the occurrence and coding of a set of basic highway network forms.
4. **Local Roads:** The framework needs to include in it detailed enough representations of the highway network to meet the needs of local roads.

From these individual recommendations, the following overall general recommendation for spatial representation may be made.

In general, any proposed LRS solution needs to have the following characteristics:

1. It provides a rich and robust enough set of tools to handle a diversity of transportation circumstances, but not so complex as to be incomprehensible or unmanageable
2. It is readily ‘implement able’
3. It provides for the storage of the relevant time information so that temporal operators may be used throughout.

These general requirements for LRS are expanded in a late section.
10.4.8 Time:

As reviewed in Chapter 7, which was dedicated to review the consideration of time, there are several types of time (including as with location, absolute and relative) and types of requirements for temporal analysis (e.g., point, period, etc).

The work carried out on time indicates that a set of temporal operators needs to be provided to meet the particular needs of all sections of the transportation information communities, but particularly those that deal largely in real time operations, such as the transit and vehicle operation communities.

Temporal operators would allow analyses such as, “It is 6.15 pm, where on the route is bus 66?”, or, “Did the bus reach this timepoint correctly?”. This thesis did not consider the detailed development of an exact schema for temporal operators. It did however give consideration to the inclusion of appropriate temporal data so that a class of temporal operators can be more readily formulated to meet particular application needs (see Appendix G).

The DOTs investigated in the Case Studies (see Chapter 7 as whole, and Chapter/section 7.4 reviewing the Case Studies, in particular), have all found some way to make temporal comparisons. These methods were fairly limited in use though. An improved framework should provide an enhanced set of methods for undertaking temporal comparisons. In particular, a LRS toolkit should:

10.4.8.1 Manage Changes to Location References over Time

All LRMs (kilometer point, link/node, control section, etc.) are subject to changes in their location references over time due to realignments and refinement of offset measures. For example, when realignment shortens a curve any ‘downstream’ offsets must be adjusted. This generally requires a system for notifying all data managers using the LRS of any updates to location references, so that they can keep their systems up-to-date and synchronized with other data systems.

Although it is sometimes considered desirable to maximize the stability of location references over time, the use of computers for automating updates to the LRS has made this less of an issue than it was in the past. Today, it is more an issue of how updates to the LRS are managed, both within an ITIS and between different LRS users.

Of note, the only essentially permanent type of location reference is to assign a unique, random identifier to each location (i.e., every intersection, traversal end point, traversal reference point, point event, and the end points of every linear event). The traversal(s) and offset(s) corresponding to each location become attributes of the location that may change over time, while the permanent identifiers remain unchanged. This system has been used as a method for establishing a permanent key field in relational database implementations of LRS.
10.4.8.2 Support the Management of Historical Data

One of the major challenges in linear referencing is the difficulty of comparing past and current conditions due to changes in location references over time. For example, a link may be reduced in length due to construction of a new interchange, although it keeps the same reference identifier (based on its 'start' node). Traffic volume data from the 'old' version of the link can no longer be compared to the 'new' version, due to its changed length. Management of changes to location references can be extended to the management of historical data. This can enable trend analysis (the comparison of conditions between two points in time) and thus the determination of where investments in the transportation system have had the greatest benefits over time.

Adding time-stamps to objects will increase data storage requirements; however, by smart coding techniques (such as using pointers to predefined block creation dates, etc.) these increased requirements may be minimized.

Recommendation: A LRS tool kit should in short as a minimum:

1) Spatial Elements: Include time stamps for all spatial elements.
2) Spatial-temporal Operators: Create a set of network focused spatial temporal operators. In particular, it should account for time-to-place and place-to-time analysis as well as time period analysis.

The topic of time is very closely related with the next topic, data maintenance, as temporal maintenance of changes in state are a key part of that topic.

10.4.9 Maintenance

LRS maintenance issues were considered in Chapter/section 6.10. LRS data maintenance issues were also implicitly considered within the more detailed consideration of Time in Chapter/Section 7 and in particular Chapter 7.4. A common challenge with all GIS datasets, including transportation networks, is that of Geometric Change and update. With Geometric Change, a realignment occurs in a portion of the highway and thence downstream LRS traversal offset distances are changed. As with any LRS system, an upstream change will require a downstream recalibration of downstream distances.

Linear LRSs are challenged by the problem of managing updates to the LRS and keeping various event databases synchronized with the LRS control database (see Chapter/section 7.4). These problems have led to various techniques for minimizing the impact of updates to the system, including:

1. Use of control section or link-node traversal organization schemes (fewer roadway sections are impacted by a localized update)
2. Use of mileage equations (avoid updating of downstream measures)
3. Date stamping of all LRS updates (so that event locations don’t need to be rectified, but this complicates data analysis)
4. Integration of event databases and LRS control in a unified application (minimize the problem of updating and synchronizing remote event database, at least for mission critical information).
Today, using automation techniques and database technologies, these problems are much more easily managed than in the past. The apparent trend today, as evidenced by Missouri DOT’s integrated Transportation Management System, is to manage linear referencing by traversals based on the numbered and named roadways that are most familiar to end users. Introduction of ‘intermediate’ traversal schemes (such as control sections) is avoided to minimize complications in data collection, analysis and reporting procedures. Likewise, use of mileage equations is avoided as these ultimately complicate both data management and data interpretation and analysis by end users. Updates to the LRS control and to event databases (integrated and remote) are managed through automated routines, and access to historical data is provided through the system design. Conversion between different linear referencing methods is handled by the centralized system. The increased support of dynamic segmentation and management of linear referencing by GIS adds additional support for this trend.

As with the focus on engineering levels of data storage and accuracy, given the wider scope of issues in this field, it may be argued that in fact this matter has sometimes got a relatively highlighted attention. Obviously, if one is undertaking accident analyses along corridor of Route 30 from 1960 to the year 2000, the ability to include all data even where the highway alignment has changed (or new sections added), can be highly useful and important. In the wider contextual frame, the following field practical concerns need to be noted:

1. **Creation of the Base Network**: Many DOTs are still putting in full place their 1:24,000 datasets. The use of GIS for the first time clearly indicated that many DOT base networks in use had many missing segments and links, or had segments that had been significantly miscoded for years. A concern with historical data and data maintenance was, from a more academic standpoint, “a good one”. However, the real practitioner struggle for many DOTs was to first put together a single reasonable quality network representation that could act as:
   a. The current-day base network representation
   b. Provide a satisfactory base on which to undertake forward data maintenance activities

   Certainly, these issues existed in several of the DOTs in the Case Studies and in other DOTs visited. For example, Iowa DOT currently has as many people (i.e., 8) working full-time on the set-up of the first more accurate and complete DOT 1:24,000 centerline field, as they do LRS. When DOTs have clearly got one such network in place, and this has been tested and used for a period, then it is likely that further practical focused attention will come on undertaking historical comparisons. It is difficult to do historical comparisons and meaningful data maintenance without having a current base network of worth in place.

2. **Analyses Undertaken**: While there are examples of analyses undertaken that clearly benefit from reference to previous historical data, in fact many of the analyses carried out in DOT’s are focused on their present day data networks. For example, many of the maps produced will show current year highway condition, accidents, congestion, traffic flows, etc.

3. **Annual Update Cycle**: For a number of logistical and operational reasons, it would appear that DOTs to date have had their user needs reasonably met if they undertake an annual update of the network. These reasons include that:
a. **Diversity of Update Sources:** Updates and changes are coming in from a number of sources and need to be correlated and agreed.

b. **Available Staff:** Most DOTs have had significant staff cuts in recent years, as well as political pressures from contractors lobbies to put a high a proportion as possible of available funding “out on the street”.

c. **Annual “Log” Distances:** There are official log distances agreed for funding and other purposes on an annual basis.

Thus, rather than undertaking constant maintenance and updates, changes to the network may be stored and input annually at a given annual time period.

To deal with the issues that stem from data maintenance, there are a number of additional different approaches, none of them “complete” approaches, all of which have strengths and weaknesses, that help address the issue of doing network comparisons when data maintenance has occurred. From the work carried out in this thesis, they include in summary:

1. **Spatial Lowest Common Denominator Approach:** Spatial coordinates may be held as properties of the “lowest denominator spatial objects” (i.e., as most commonly reviewed here, “highway segments”). The appropriate definition of network segments may be somewhat application-dependent, depending on say whether for example for highway maintenance or transit operation. However, from the data management perspective proposed in this thesis, the assumption here is that they are first “logical units”. All higher order network based geometries and topologies are created from lower order spatial entities. Thus, if a realignment of segments or multiple segments occurs, a realignment of the higher-order cartographic elements that are built on these lower order elements needs to occur. (This processing should be facilitated by the COTS software). This approach, or simple versions of it, currently effectively occur in many DOT’s. This does not provide a significant overhead on processing as it may practically be only undertaken on an annual basis.

2. **Route Calibration Tools:** Route calibration tools allow the relative positions on routes to be estimated where changes in geometry occur. Existing COTS software contain a basic set of route calibration tools. Again, the exact needs for route calibration tools may be application area specific.

3. **“Just in Time”**: When data maintenance on a network occurs, and there has been geometric update, tools of “network conflation” may be used to facilitate cross-network comparisons. This approach in short assumes that different complete networks are maintained for the different analysis years. The use of network conflation tools was reviewed in Chapter/Section 4.4.4.

While given reasonable consideration in this thesis as one of the LRS key topics, clearly the area of data maintenance and subsequent temporal comparison is one example of that worthy for much more detailed and focused research. The area will become a topic of higher practical concern in DOTS when quality base networks are clearly well in place, which has not been the case to date. The area is identified in the further research section (see Chapter/Section 10.6.2).

Some further consideration of this topic is given below in Chapter/section 10.5.6.

**Recommendation:**

1. DOTs need to put in place explicit LRS data maintenance procedures.
2. The activities are best focused on when a base network is standardized and in place.

10.4.10 Institutional Factors:

At the local agency level, while technical considerations are important, the wider context for the use and adoption of any LRS solution is also very important. Chapter/Section 9 reviewed institutional issues as they relate to LRS.

In short, a ‘first rate’ LRS solution, in a poorly aligned institutional context, may be less successful than a possibly “second rate” LRS technical solution, but one set in a well-aligned and supportive institutional context. At the national level, a major determinant of the operation of the whole LRS field is that there appears lack of will to support a national LRS integration or at least best practices effort. If such an effort was to occur, the major beneficiaries of this might in the first instance be the DOT’s. At the present times, with pushes from different sub-communities to develop the NHCRP 20-27(2) model (from the GIS-T community), the ITS Datum (from the ITS community), and for the BTS model (such as any federal encouragement or direction is provided), a reasonable approach for many DOTs is “stasis”.

Recommendation:

1. Further explicit research needs to take on appropriate GIS-T/LRS institutional approaches
2. GPS practices as a whole need to be better institutionalized within DOTs
3. A national level LRS synthesis and set of best practices need to be agreed and provided to DOT practitioners on:
   i. GPS
   ii. LRS.

10.4.11 Summary: Diversity, Flexibility and Toolkit

The need for flexibility in the LRS toolkit is probably the most generic observation provided here.

The analysis of the different road data models (as conducted in Chapter 5) indicated that each had really been designed to meet the needs of one particular user community (e.g., the ITS community, state DOT’s, etc.). Also, any one model proposed by any one of these communities typically would have within it one very set way of defining relationships, e.g., “a route is made up of one or more whole links (and only whole links)”.

Transportation is a set of diverse modal and information sub-communities (as laid out in a little detail in Chapter/section 3.5). The field is multi-disciplinary – that is, it benefits from multiple viewpoints and academic disciplines. Transportation practitioners and their application providers would appear to need “application toolkits” that can be utilized in a format appropriate to best implement LRS in a particular transportation sub-community.

10.4.11.1 Support Multiple Linear Referencing Methods (LRMs):

As one example of this, LRS should support multiple LRMS. Different transportation data users typically have different preferred methods for specifying locations on the transportation network.
A robust LRS enables different users to enter and report roadway-related information by methods that are appropriate for their particular tasks (although the data may be stored by a single, standard referencing method). For example, safety offices often prefer to locate crashes relative to intersections. In contrast, traffic data is often located along sections of roadway with uniform traffic volume, typically by begin/end offsets along traversals corresponding to named highways. As another example, maintenance staff are often required for accounting purposes to record the locations where they performed their work. A snowplow driver is greatly impacted if he must record the locations of his route as a long series of links and offsets. Obviously, he would much prefer to record one or several ‘snow plow route’ numbers with corresponding offsets. A robust LRS can simplify data input and access for end-users.

10.4.11.2 Multimodal Networks:

Chapter/section 6.11 covered multimodal aspects. A LRS should meet the needs of the wider transportation communities and modes. A robust LRS is not limited to the roadway network, but supports any mode of transportation on a linear network (railways, waterways, etc.). While many LRSs are originally developed for roadway systems, it is desirable to have an LRS that can be readily extended to other modes of transportation, and which enables multimodal networks.

10.4.11.3 Alternative Types of Route Construction:

A LRS should support different types of route as constructed by different transportation modes. Similar to the underlying construction of a network that has highway forms that resemble those that occur in the real world, so a consideration of the multimodal potential of LRS indicated that a greater flexibility was required in the set-up and maintenance of a wider set of transportation network types and network routes (See Chapter/section 6.12). It was found that transit agencies in particular required a great degree of flexibility in the creation of routes. Ideally a LRS would contain a transportation network route assembly tool kit and set of update and maintenance procedures for this.

Any solution needs to be in a toolkit form to meet the diverse and changing needs of the wider transportation community.

In developing a LRS framework for potential use by a larger set of potential sub-communities within transportation, the biggest single generic wider community need was for model and application flexibility. In short, the maxim “no one model form fits all needs” seems to particularly fit the LRS area.

Any LRS adopted by a transportation agency needs to be fully evaluated against the above specific criteria. In addition, a transportation agency needs to be further sensitive to particular local goals and issues, including legacy practices and investments. There are other factors that could be considered in providing requirements for any improved LRS framework. The above ten appeared the most critical ones on the basis of work carried out here.

Given the diversity of the field, and the many uses for LRS, probably a much more detailed set of practitioner reflections could be drawn out. However, the above emerged as a key set of reflections on the practical state of the field today.

Recommendation:
1. A key general design concern of that framework is that it should offer significant flexibility to meet the diverse needs of the wider transportation community.
2. As one practical instantiation of this, networks and routes should be able to be able to be created and assembled in different ways and with alternative assemblage schemas.

In particular, LRS should support:

1) Multiple LRMS
2) Multimodal networks
3) Alternative types of route construction.

10.5 New LRS Conceptual Framework: A Basis

The previous section provided recommendations on existing LRS practices. On the basis of the work carried out in this thesis, and the subsequent recommendations for improved working practices, in addition a possible new basis for developing LRS is tentatively proposed here.

10.5.1 Background Considerations to the Proposed Approach:

The Romans invented the basic LRS off-set schema 2000 years ago to help position themselves on 55,000 miles of basically uniform linear feature. Since then, in the 20th century highway data managers have adopted a number of variations of the LRS “off-set game”, with for example the use of mileposts, mileage equations, backwards and forwards calculations, etc. However, the core basis of the LRS “mathematical game” (that is, the core of the LRM) remains fundamentally the same.

In the latter half of the 20th century, (and, in particular, in the last 10 to 20 years), highway have begun to more commonly introduce much more complex highway forms, as exampled by the highway cloverleaf. The need to data manage highway facility data at much more disaggregate levels has also been created. Use of spatial data collection and management technologies (such as GPS and GIS) has made such disaggregate analysis work seem both possible and desirable.

Recognizing transportation as an essentially linear science, this thesis investigated LRS as it's focus. In particular, a main end-goal of this thesis was to give as practical practitioner advice on LRS -- and to draw out areas where further research needed. It also kept a sense of LRS being a member of the class of "spatial messy problems" and the need to develop forward-going research methods (RM) for such problems.

The section immediately above (Chapter/section 10.4) synthesizes some of the advice and suggestions on specific LRS observations suggestions, advice within the context of current LRS practices and frameworks. This section briefly reviews an alternative framework for conducting LRS in future. This framework reflects:

1. Developing User Needs: Appears to address many of the user-needs and field recommendations identified above for LRS
2. Developing the Technical Frameworks: A possible review of the existing recommendations made for better practice LRS which are principally aimed within current working frameworks.
A research thesis can be potentially be 'hypothesis generating', or, 'hypothesis testing'. As one of its recommendations for forgoing research, this thesis created a hypothesis that given the modern-day development of highway forms:

1. **Existing Methods Fine**: Existing LRM's are, "all basically operationally usable"
2. **Tie to Cartography Issue**: Help is needed tracing LRS's through more complex highway forms (and local roads). Many LRS issues recorded in the field seem to be problems of relating the underlying network, or matching the placement of traversals with more complex real world transportation forms.

### 10.5.2 LRS Design Drivers (CSF's)

The proposed technical OO framework (outlined in Appendix G) acts as *one possible synthesis* for this thesis across the ninety technical (and institutional) observations and recommendations observations (collated in Appendix H). In system or software design parlance, some of these concluding observations drawn from across the thesis might be viewed as, or lead to, the definition of more formal, critical success factors (CSF’s). CSFs are often technically specified through a set of formal system "shoulds". The additional work undertaken in Appendix G is one approach to "reflecting" on the, “so-what” of the wider body of research work carried out in this thesis. A higher-level conceptual framework is tentatively proposed based on the research findings of this thesis. This additional work was undertaken in part to underline some of the main findings of this thesis.

A set of ten key findings from the thesis were reviewed. From this, from an application design perspective, a summary set of ten key design issues or CSF’s for a potential new basis for LRS are outlined in Table 60.

The ideas presented here represent a combination of three related conceptual transportation network forms:

1. **A “topologically useful version of a network”**. A set of route or traversal elements that could operate on it, that reflect the needs of the wider transportation community, are proposed.
2. **A “data management form of the network”**. Substitutable ways of representing the underlying network are created that reflect data management needs.
3. **A “multiple cartographic representation form of the network”**. The name of the unit is viewed as the master property, not the geometry or geometries, which are viewed as a property.

It is proposed that the network could evolve from a simple street centerline representation (as typically currently presented) to a more complex set of pre-encoded “geometric representations”. Chapter/section 3.5.3 reviewed different cartographic scales and map representations, Table 9 reviewed the use of different map scales and projections, and Figure 8 showed levels of network representation. The following Figure 74 shows some alternate network intersection representations. The lexicon or toolbox of network parts could be extended and improved with time and transportation field use.
## Table 60 LRS CSFs and the Proposed Framework Response

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<th>#</th>
<th>Factor (CSF)</th>
<th>Proposed Framework - Response</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Planning and Management use</td>
<td>Largely geared to planning and data management concerns (vis-à-vis the geometric maintenance of data)</td>
</tr>
<tr>
<td>2</td>
<td>Variable Spatial Accuracy and Display</td>
<td>Allows network elements to be maintained and displayed at varying degrees of accuracy</td>
</tr>
<tr>
<td>3</td>
<td>Line Representation</td>
<td>For many purposes in the framework, connections between nodes may be shown as straight lines</td>
</tr>
<tr>
<td>4</td>
<td>Cartographic Form</td>
<td>An initial set (or toolbox) of cartographic/database forms are proposed of highway and intersection elements</td>
</tr>
<tr>
<td>5</td>
<td>Time</td>
<td>Potentially all spatial elements can be time-stamped. Time attribute may be instantiated by class or temporal operators.</td>
</tr>
<tr>
<td>6</td>
<td>Route Construction</td>
<td>Routes may be constructed from a variety of sub-element types, to fit the particular needs of different modes or transportation communities</td>
</tr>
<tr>
<td>7</td>
<td>GPS Data Collection</td>
<td>The approach would appear to meet the needs of GPS-equipped data collection vans which generate large volumes of traversal based data</td>
</tr>
<tr>
<td>8</td>
<td>Flexibility</td>
<td>The model form implied by the framework is very flexible</td>
</tr>
<tr>
<td>9</td>
<td>Local Roads</td>
<td>By providing for a greater detail of link and intersection types, facilitates the encoding of local roads</td>
</tr>
<tr>
<td>10</td>
<td>Object Oriented Approaches</td>
<td>Framework based on an OO approach</td>
</tr>
</tbody>
</table>
Figure 74 Alternate Intersection Representations
Since for example the US Census Bureau DIME file was developed to TIGER, the transportation community have in some measure already dealt with the concept of single objects having potentially multiple, spatial representations. The Census TIGER file, a national database, produced first for enumerators, but utilized by many in the transportation community for example assembling demographic TAZ data, has straight line and/or increasingly shape detail, for many areas of the country. A set of spatial and cartographic rules needs to be in place to deal with all of the cases that may exist, that for example, account for maintaining spatial integrity and dealing with cartographic interference, etc.

It has always been the way in this field that "special cases", "are the thing" (i.e., the norm). A basic function for much environmental and land-use GIS work, Polygon Overlay in GIS (i.e., the basic algorithm being 20% effort) did not work until developers figured out how to deal with the “special cases” that existed around this topic, for example, "the island within island problem" (i.e., 80% of the effort). General experience, as well as the research undertaken here on the pathologies of LRS, shows one cannot expect to figure such “next round” issues without extensive field-based research and consideration. The thesis has however shown the basis of a multi-faceted, user-focused approach to further examine this and similar spatial field problems. And without doing the next phase of research, at best we may just offer some possible technical hints from work completed to date.

10.5.3 Suggested Schema

What is proposed here, in response to the above needs and observations, is a Transportation (network) Lego.

A hypothesis generated is to create a Transportation Lego. The components (entities or objects) of this would in brief contain:

1. **Geometry**: Ability to contain geometries or geometries
2. **Topology**: Other critical and useful topological (such as connection to adjacent Lego)
3. **LRS Trace**: Facilitation on how to trace LRS through the highway entity (particularly if more complex)
4. **Attribute**: Attribute information describing some of the characteristics of the Transportation Lego.

The Lego™ may actually be better actually more accurately conceived of as a "Brio train track piece". Brio™ is a wooden railroad with a set of interchangeable, interconnecting linear track pieces. As not all individuals may be so familiar with the Brio™ name and equipment, the name ™ of more common currency) is used here. However, Transportation Lego pieces are not linear or transportation focused, though retaining the connotation of, modular “building blocks”.

Pragmatically, the justification for the adoption of such a Transportation Lego is unlikely to rest on LRS alone, as other critical transportation user needs would logically need to be incorporated (for example, for network flow modeling, etc.). It is possible but unlikely that a transportation agency would want in the longer-term to support multiple transportation Lego’s.

Key issues for this proposed Transportation Lego include:

1. **Creation**: For example, how to partition (segment) the network?
2. **Maintenance:** For example, how to deal with geometric update?

3. **Use:** For example, how to represent the Transportation LEGO pieces at different scales?

Future LRS research would more fully develop and test the design of the Transportation LEGO pieces. The observations here are based only the review of LRS provided in this thesis. Defining the use, setup and operation of the toolkit Transportation LEGO will involve thinking through and data capturing many of the "special cases" reviewed in this thesis (See Chapter/section 6). As with the so-called "special cases" with LRS, may not really be special cases at all, just "cases". There is a rich set of research issues here to be more fully developed beyond this thesis, but some working thoughts are provided here. The research methodology to be used in such further work might clearly:

1. **Recycle and Develop the LRS RM:** Follow the line on analysis and research method invented for this thesis. As with this thesis, defining Transportation LEGO will be another classic case of investigating a spatial messy problem (see Chapter/section 3.2.1).

2. **Continue A Strong User Needs Focus:** In particular, reflect the notion that the answers to many of the research questions posited above will not just be "mathematical answers" (for example, "how to do geometric update?", "scales issues", etc.), but be based on a thorough understanding of the full range of likely user needs and the full transportation context.

It is not the intent here to provide a detailed justification for the approach, which should be the subject of continuing thesis or theses. However, to provide some more reference for the idea, some tentative observations and suggestions on the above points are summarized in the following four sub-sections. The following sections give some ideas for the creation and maintenance of the Transportation LEGO, but these are provided in very "initial vision" form.

### 10.5.4 Outline Data Form

The exact form and set-up of a scheme of Transportation LEGO should be determined by detailed user requirements analysis and research. In this context of at least describing the vision to a reasonable level of initial detail, the following may be taken as possible, indicative, characteristics that would typically be associated with the Transportation LEGO pieces:

1. **Anchor Reference Points (ARF):** Each Transportation LEGO piece would be bounded by some form of anchor reference points. A brief indicative description of the possible set-up of these is included below. The ARF may contain direct x,y data, or, be derived estimates from more secondary sources (e.g., derived from other anchor points). The ARF may be electronically tagged in the field to delineate the stop/start between each Transportation LEGO.

2. **Control Section Form:** It may be regarded as somewhat analogous to the current use of "control sections" by some DOTs. In particular, each Transportation LEGO piece may be viewed as having the function of a "logical data management unit".
3. **Local Linear Reference**: It may be possible to locally linearly reference within Lego pieces. These references might be combined with distance (in either direction) along a traversal to the **Transportation Lego** piece. The referencing might yield different numbers for different associated geometric representations of the same segment. This would occur if for example an intersection was shown as a simple stick intersection, or, as detailed geometrical layout.

4. **Topology**: Record of route membership might be done at the route level. Alternatively, or in addition, each **Transportation Lego** piece could record (or inherit) which adjacent **Transportation Lego** piece it is connected to, and possibly other topological information (e.g., which routes traverse it, etc.).

5. **Geometry**: It may maintain multiple geometries. Metadata is associated with these geometries. The contents and requirements of this metadata need to be clearly specified.

6. **Display Forms**: Each class of **Transportation Lego** piece has a set of display forms that may be associated with different map scales and associated geometries. Each unit may be displayed in default supplied forms. These pre-supplied forms may facilitate the display of field forms indicated for example in Figure 74.

7. **Linear Path Trace**: Each **Transportation Lego** piece is provided intelligence how to trace a LRS path through it, when supplied a traversing route. For example, a cloverleaf knows which ramps to trace a traversal when supplied the east-west and north-south aspects of a maintenance route, or, a cul-de sac "knows" that the maintenance route traverses anti-clockwise around the turning circle.

8. **Attribute Data**: A standard set of default attribute data or characteristics is stored with each **Transportation Lego** piece. These would correspond to those items normally collected by the DOT e.g., pavement type, lane width, etc.

9. **Universal Operators**: Each unit may be operated on by “system level”, “class” or individual unit level operators. These may change default characteristics, provide update, etc.

10. **Generalizability and Substitutability**: Each unit should be readily switch-able with another form or forms. For example, one ten-mile section of highway which is represented by one **Transportation Lego** piece, “Divided Highway (Type 2)”, might be switched in three pieces, which might be for example:
    a. **Divided highway** 4.8 miles long
    b. **Cloverleaf intersection**. 0.2 miles wide
    c. **Divided highway**, 5.0 miles long.

These new units should inherit properties that are consistent with the original Lego piece and the adjoining network. N.B. The set-up of the logic schema to operate with the **Transportation Lego** is as important as the definition of the **Transportation Lego** itself.
10.5.5 Data Form Creation:

The following ten steps are a summary of some of the possible key steps that might be taken by a transportation agency to setup a TRANSPORTATION LEGO.

1. **Maintenance of Current practices**: Current highway maintenance processes would be kept in place until the exercise below is fully completed and tested.

2. **Inventory of Current Highway Parts**: The agency should review its current inventory and potential needs for highway forms across its current and proposed networks. The review should include forms that are not currently modeled, but which may be needed in ongoing work. Advice on this should be gained from example case studies that are developed for use with the TRANSPORTATION LEGO.

3. **Basic Toolkit Selection**: A toolkit of acceptable highway (transportation network) parts would have to be adopted. The form of this should be appropriate for the particular uses and activities undertaken by the agency. To gain experience from wider agency activities, it is unlikely that any one agency can best research, refine and setup such a toolkit within COTS GIS, but instead the toolkit might be exogenously provided. That is, the toolkit might result from a wider vendor research effort or other nationally-led research effort. The toolkit would focus on the high order classes ("super classes", and provide examples of particular derivations for such classes and individual objects). The TRANSPORTATION LEGO would contain discernible data management “parts” and would likely correspond to those features discussed in a number of locations of this thesis (for example, Table 1, in Chapter 1, and Appendix G, etc.).

For example, the cloverleaf super class might contains basic default geometry or geometries, (following for example the “Highway Design Manual standards), a matrix of the characteristics of potential LRS traces through the intersection, topological information (including allowed potential connections) and attribute information placeholders. A particular class ("Type 1") of Cloverleaf might be a "Simple Cloverleaf". A particular instantiation might for the type of Cloverleaf between route 30 and route 41, that is of say "Type 1A".

4. **Toolkit Mapping**: There would be a mapping of current transportation forms against the core TRANSPORTATION LEGO set. Sub-classes and particular forms would be set up for network coders to meet particular agency requirements. Coding methods or “tricks” might be employed to match real world forms with available classes. For example, if a cloverleaf did not have one “normal” ramp that was available in the standard TRANSPORTATION LEGO cloverleaf set-up, this ramp might be coded as “non-operational”. (Provision should be made for “non-operational” coding).

5. **Creation of Classes of Anchor Reference Points**: To best operate the TRANSPORTATION LEGO schema, it is likely that a number of classes of anchor points may need to be developed and adopted. This is likely to be based on some research that would determine exactly how such points should interoperate. *An example* three-tier anchor reference point class might for example be:
6. **Network Segmentation**: The agency transportation (highway) network would be segmented to be completely mapped into the adopted TRANSPORTATION LEGO. This would involve creating “highway database maintenance breakpoints”, or, “pseudo nodes”, where one data management point ended and the next began. The preference would conceptually be for having one of the types of anchor reference points as described in the previous point, above. However, precise working rules for this would need to be described.

The creation and maintenance of the delineation points may in fact be seen as the schema “major commitment” and major issue with the approach. (The highway breakpoints could be viewed as possible replacements or alternatives for milepoints). In short, the whole network has to be segmented into the recognized toolkit forms. A instantiation in single form could be, for four examples:

   a. A tenth of a mile section of highway, or,
   b. One ten-mile section of divided highway intersection/intersection, or,
   c. A simple intersection, or,
   d. A single complex cloverleaf.

Rather than having physical markers in the field as has been the custom to date for 2,000 years or more, consideration might be given to delineating the breakpoints between TRANSPORTATION LEGO pieces with electronic markers or electronic mileposts. These markers might be manufactured quite cheaply, if done so on a larger scale. They might be objects that can be detected by set classes of sensor signals at perhaps relatively shorter range. For example, sensing distance for the TRANSPORTATION LEGO markers might be:

   1. **Minimum**: The width or road (i.e., passing detector vehicle)
   2. **Medium**: The average distance between markers
   3. **Maximum**: The maximum distance between markers (i.e., or use in wider area network location).

This form of operation might thus might tie in quite well with their use in an ITS context (see the review of ITS in Chapter/section 3.5.8.4). If appropriately developed, combining data management and operational ITS locational concerns would seem to be a major potential plus to the scheme proposed here.

Segmentation schema are likely to be largely driven by transportation agency user needs, in particular their recognition of their needs for highway data maintenance and the location of existing highway maintenance “control sections”
and highway features. (The set up and use of these was covered in Chapter/Section 4.2.3 on Traversals). Spatial analysis tools, including for network characterization, may provide some assistance in the design, set-up and calibration of automated tools to help guide the segmentation process. Network characterization tools may depend in part of the use of Network Statistics, as are briefly exampled in Appendix D.

7. **Assignment of Geometries**: Initially this could be done through mapping of current "log" highway forms to the TRANSPORTATION LEGO, and then instantiating this with actual geometric data as this became available. The different geometries would be clearly associated with meta data, including source, date of creation, etc. The assignment of geometries would in large part be concerned with:

   a. Maintaining the various accurate set of geometry that come available
   b. Setting display forms for the TRANSPORTATION LEGO to operate at different display scales. The schema would include default parameterized forms for this.

The display forms would be set up and designed by careful testing in the overall development of the schema. It is likely that common cartographic conventions will be followed, as most DOTs already largely follow USGS mapping conventions ("at this scale, show this, etc.").

   l. e., there are no orphan parts

Figure 75 briefly indicates in outline some of the potential display forms for intersections. These might evolve from very simple sketch forms to more detailed representations. As more detailed information becomes available more detailed network forms may be encoded.

8. **Accuracy Measures**: Each geometry would have to have accuracy measures included as part of the metadata associated with the object. A practical part of the schema – in fact an equally important co-part – might be the development of advice on accuracy measures to be associated with each part of the TRANSPORTATION LEGO. Such advice is missing today even without the use of the new units (for example, Chapter/section 4.5.1 reviewed that the fact that while the physical use of GPS is understood, placing the resultant data in an institutional context is not so well understood. Accuracy measures can include not just physical measurement accuracy, but logical and topological accuracy, etc. The use of the TRANSPORTATION LEGO cannot be expected to solve this issue independently (as it has many contexts), but may in fact act as one possible mechanism for providing a transportation agency institutional solution path or context. The TRANSPORTATION LEGO needs to have a Field Manual associated with it, and consideration of accuracy measures would be a key part.

9. **Automated Network Checking**: The built-in integrity and error checks would be at least three different levels:

   a. **Network level** – for potential example, it may be system -level set that cloverleaves may only join with divided highways or

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Figure 75 Example Potential Intersection Forms

accurate than 1:24,000 may not be used in display until a consistent set of sub 1:24,000 data is available.

b. Route Level - for potential example, a system level check may indicate that it is not permitted to join a detailed engineering level representation of a segment if this happens to be available with an adjacent segment if such detailed representation is not yet available for that segment.

c. Object or Entity Level – for potential example, a cloverleaf entity may not be joined directly with a simple highway entity (only divided highway).

A set of network validation and checking tools would thus be made available with the schema. This might for example check that:

1. All parts of the highway network are coded into TRANSPORTATION LEGO form.
2. The is a logical consistency in adjacent TRANSPORTATION LEGO
3. All parts of the network are connected (i.e., there are no orphan parts)
4. There was no spatial interference in the geometries provided in adjacent (or even non adjacent) highway forms.

A list of areas to check would be provided by TRANSPORTATION LEGO automated network set-up tools. As already mentioned in Point 7 above, the use of Network Statistics, as described in Appendix D, and also mentioned in the outline example in Appendix G, may also aid in the setup of these tools.

10. Manual Checks: While the automated checks should cover as much of the necessary data setup checking as possible, manual checking by end-users would be still be required.

The process might start with the creation of TRANSPORTATION LEGO for a “spider network”, such as the Interstate system, and then be extended to state roads then local roads.

On satisfactory completion of the major implementation steps, with iteration as necessary, data transfer to the TRANSPORTATION LEGO system would be made at this time by the highway authority.

10.5.6 Data Form Maintenance

To facilitate further consideration of the basic idea of the TRANSPORTATION LEGO, some possible ways it might be developed have been outlined above. Until these units have been put in place it is still further difficult to be definite, even in outline, on exact data maintenance procedures that need to be put in place with them. However, it needs to be recognized that this is an important topic and that no design can be considered complete until it includes full consideration of it. The five items below indicate some of the topics of data maintenance that will have to be carefully considered.
1. **Geometric Update: Basic Update Check.** As new geometry is provided, basic checks could be included to check its validity. (For example, bridge location data collected by inexperienced users has notoriously been, “in the ocean”). Spatial “region consistency” and other checks could check basic validity.

2. **Associated Mapping Form:** As new geometry is provided, new mapping forms for each TRANSPORTATION LEGO unit needs to be associated, appropriate for the different typical mapping scales.

3. **Route Recalibration.** As new and improved geometry is available, methods need to be provided to include it. These may include in short:
   i. “*As is*”: The data is recorded with the form, but no wider system level check or integration is made.
   ii. “*Within TRANSPORTATION LEGO Unit*”: Alterations may be made for example to the way the unit is displayed. This may also be a straight substitution where for example a “node” intersection is substituted by a more detailed form, but centerline traversal distances do not change.
   iii. “*Route level update*”: If for example a distance is recorded that is different from that previously recorded a set of rules need to be set in place for causing recalibration of route distances.

   A route level update needs to work logically through a chained set of anchor reference points as indicated above. The use of mileage equations which in traditional schema for LRS has been frowned upon, may be reviewed in the light of the possible adoption of the TRANSPORTATION LEGO schema. The argument against mileage equations has been principally the difficulty of maintaining them. However, this might be improved within the context of a tightly integrated schema for maintaining TRANSPORTATION LEGO.

4. **Geometric Update: Topological Update.** New changed geometry needs to be checked that it does not invalidate existing topological structure connections. For example, in a perhaps a relatively obtuse case, but one likely to occur with centerlines being independently updated, a road that is given additional curvature might intersect another road whose geometry has not yet been equivalently updated. Checks and flags for this need to be included.

5. **Attribute Update.** Routines need to be provided to update attributes of individual objects, classes and “super-classes” of objects.

Examination of field cases is likely to show a set of “special cases” or pathologies that need to be examined and data maintenance routines included for them.

An essential realization of data maintenance is that the fundamental data update maintenance and logic issues that exist with LRS today (and tackled with such tools as, mileage equations, mileposts, anchor points, etc.) will in fact likely be essentially similar with use of the TRANSPORTATION LEGO. The principal difference with the Lego is that not necessarily that some of the fundamental issues go away, but in “encapsulation”, that is:

1. **Data capture:** The use of the TRANSPORTATION LEGO acts as a form for capturing some of the repeatable field logic.
2. **Encapsulation:** Some of the details of the operation of this may, as appropriate, be hidden from various classes of transportation end-user, who may not be interested in such.

This field information potentially contained in the TRANSPORTATION LEGO may be regarded as one form of, "higher level metadata". The TRANSPORTATION LEGO allow another level of abstraction to occur to route, super-route, etc.

As described above under “TRANSPORTATION LEGO Creation” (Chapter/Section 10.5.5), the use of Network Statistics (as briefly reviewed in Appendix D) and the use of automated tools, such as network connectivity checkers, (as briefly reviewed in Appendix G), network simplification and network generalization tools (some general statistics for which are reviewed in Appendix D), may aid in the development of support processes for data set-up and maintenance. The aim will be to automate and assist the process as far as possible, realizing that full automation (with "messy" real world data) is unlikely. (For comparison, the network conflation process, after two or three years of intensive application tools development and field experience was pushed to the around 90% automated network match level between two broadly similar, but different, urban area networks. However, the process which formally took many person-months, can now be undertaken in a few hours of processing time).

### 10.5.7 Schema Potential

About 15 basic principal highway “types” or parts (including intersections) were detected in the DOTs reviewed in this thesis. (Appendix G briefly reviews the development of these highway types in an object-oriented form). The five main general benefits and justification for the development of the schema are that in short it potentially facilitates:

1. **Network Encoding:** This covers the physical encoding and use of the network at a level that is appropriate for its use within transportation planning information systems. The types or object should be set-up to accommodate improved and more detailed network geometry’s as they became available.

2. **Network Error-checking and Logic Checks:** This covers the creation of a basic set of behaviors for error and logic checking to be associated with these highway forms or parts. For example, an intersection might check that it is connected topologically to adjacent and appropriate forms of network links (a cloverleaf would most logically be connected to a divided highway, etc.).

3. **Network Presentation:** The network form may be encoded with behaviors for display appropriate for different settings. For example, this may often apply to different map scales, where a cloverleaf intersection might display as a node at 1:100,000 scale, a simple cloverleaf form with ramps at say the 1:24,000 scale and in a more complex form with lanes and other additional information at the 1:12,000 scale or below.

4. **Network Analysis:** The use of the TRANSPORTATION LEGO facilitates the set-up of analysis routines that may work directly on these highway forms. This may facilitate analysis that could be done at present with more complex queries, but may be done more directly with the use of these highway forms. For example,
“create detailed intersection layouts for the CBD and leave all external
intersections as nodes except where they occur on divided highways.

5. **Network LRS:** LRS may be more readily applied through more complex highway
layouts and intersections where predefined highway types exist. For example,
Highway Maintenance Route 1 that traverses from route 30 (east-west) to route
35 (south-north), through cloverleaf Type 1 would automatically “know” which
of the ramps of the cloverleaf it had to traverse, when moving say east-north.

Thus, the use of the network types may have potential uses outside of LRS alone, though most
transportation agency network data storage is currently based in some form of LRS. However,
the fuller justification and detailing of the **TRANSPORTATION LEGO** implementation schema would
be best undertaken on a wider set of criteria and issues than those covered in this thesis, that is,
focusing on LRS alone.

This approach may in some manner be recognized as a “middle-out” strategy. It is in essence a
middle-out strategy as in short it is a compromise between setting up and maintaining the spatial
characteristics of networks as:

1. **Simple Single-line Representations** (at say the 1:100,000 or 1:24,000 scale), and
2. **Complex Engineering-level Detailed Representations** (at perhaps 1:2400 down to
say 1:100 levels).

In short, the encoding of additional network form data into a network/LRS schema allows
relevant additional detail to be encoded that is both:

1. **Feasible and Practical**, given the current limits of technology and the availability
of data, and
2. **Wholly appropriate, and relevant**, given the actual needs to which LRS based
analysis is currently typically put.

Having centerline data that is marginally more accurate may only marginally analysis, but
knowing that this section of highway is a “Divided Highway, Type 4”, (with many built-in
characteristics) may actually greatly facilitate certain types of analysis.

The **TRANSPORTATION LEGO** **covers both underlying network elements and the
construction of route elements and also attempts to fully meet the CSF needs
specified in**

Table 60. Example of the Lego, route elements and a summary of the overall model hierarchy are
given in Appendix G.

In summary, the ten main technical strengths of the approach outlined here are potentially in
short:

1. **LRS Facilitation:** It allows more detailed routing of LRS through intersections
and network special cases to be undertaken automatically. With for example
intersections, the object code can deduce the traversal path (and thence other
route characteristics, such as length, type of surface covered, etc.).

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2. **Recycle Logic:** Network and route objects and the logic they contain once defined can be reused and recycled, as well as adapted and amended for particular circumstances.

3. **Standardization:** The encouragement of standardization of highway definition by facilitating mapping into a set number of highway objects.

4. **Time-stamping:** All objects can be time stamped, in manners that may be pre-defined, and fully system supported.

5. **Implementation Support:** It is fairly simple conceptually to understand and matches parallel approaches used to model intersections within the context of transportation network flow modeling that have grown up over the last 30 years.

6. **Interoperability:** It will facilitate transportation data interoperability within and across agencies.

7. **Reuse of data structures:** It facilitates further degrees of “nesting”, which is an advantage as nearly all data entities can ultimately be further specified (e.g., Cloverleaf Superclass, cloverleaf Type 1 class, etc., Type 1A, and object cloverleaf 101 which is of type 1A).

8. **MetaData:** Data quality tags are included with objects.

9. **OO Methods:** An OO approach gives advantages in application and maintainability (see Chapter/section 3.6.5). It is more likely to be adopted by vendors.

10. **COTS Support:** The approach here has links to approaches that are being promulgated for more general international use by the OGC and OMG at the present time (see Chapter/sections 5.9 and 5.10).

The four perhaps more likely main weaknesses of the approach proposed here are that it requires:

1. **Implementation Cost:** The time and difficulty of the institutional adoption of a standard transportation object library
2. **Technical Issues:** Conversion of existing transportation networks and route systems into this format
3. **COTS Support:** In practitioner-terms, it ultimately needs vendors to support it to be field end-useful concept.
4. **Unknown Path:** The full complexity of the approach needs to be determined.

The above approach recognized that the spatial data within transportation networks have many diverse forms and “pathologies”. However, ultimately these forms have a limited number of basic main forms (and also a limited number of variants). By determining these objects and patterns coding into a set network set can be facilitated.

The operation of the scheme is in some ways no different than that used for the last twenty years with more detailed transportation network modeling packages (for example, Tranplan or TranSims), where for example intersections types are coded into asset of for example nine
categories. The fuller development of the scheme here should not just depend on LRS uses, but the wider set of potential DOT transportation applications (such as network modeling).

The approach in summary moves towards a macro/ID concept based form, rather than, a geometry form or a feature definition.

10.6 Further LRS Research

The areas identified for potential further research include at some level, many, though not all, of the areas investigated in this thesis. This research work identified the key LRS issues, resolved some, provided interim answers on many, but the larger majority require more detailed research to secure a best and fuller resolution.

10.6.1 High-Level LRS Research Topics:

Perhaps the two highest-level generic questions for LRS further is to research in detail:

1. **GPS Role:** The role and benefits of LRS in the face of GPS development
2. **GIS Role:** The practical basis for COTS spatial database technology to handle spatial data in an efficient and flexible manner (as briefly reviewed in Chapter/section 4.5.1).

At the next level, five higher-level topics of LRS seemed particularly worthy of further formal research.

1. **Local Roads:** How best to include local roads into a state maintained database and include LRS? (See Chapter/section 9)
2. **Accuracy:** How best to deal with accuracy issues in connection with LRS (see Chapter/section 6.8, and 6.10.2, and 6.11).
3. **Time:** How best to include temporal aspects? (See Chapter 7).
4. **MultiModal Aspects:** How best to allow for multimodal coding of network for modes other than auto by those who may wish to use LRS? (See Chapter/section 6.12).
5. **Dealing with Network Pathologies:** The coding of real world networks includes many variations and “highway types”, as was covered in Chapter/section 6.6, “Special Cases for Defining Traversals”.

These are examples of other larger research questions that exist with LRS, but the above seem particularly pertinent to improving field practices.

10.6.2 Detailed LRS Research Topics:

Five examples of perhaps still more technically-focused and more detailed LRS topics for further research that appeared at least somewhat more important, based on the work carried out in this thesis, include:
1. **Traversal Identifiers**: There is a need to identify and determine best practice from alternative schema for coding traversal identifiers need to be identified (see Chapter/section 6.4).

2. **Schema for Coding Ramps**: It was found in (see Chapter/section 6.6.2) that in the different DOT examples, alternative schema could be made to work for encoding ramp level data. However, which schema is optimal — that is, “which schema would offer the greatest overall benefits?” could be usefully researched.

3. **Separate Traversals**: This is a key consideration for coding divided highways. New research would indicate when their use was justified, what are the pros and cons of using them in different situations?

4. **Alternative Schema for Lane-Level Data**: As increasingly GPS equipment becomes more field accurate, even in the context of use of moving field data collection vans, now that S/A has been switched off (see Chapter/section 4.5.1), what is the potential and optimal basis for collecting more accurate, and in particular, transportation network lane-level data?

5. **Accuracy Effects of 3D**: As was reviewed in Chapter/section 4.3.2, inaccuracies occur because of 3D effects. As was reviewed in the prior section, these effects may not be as great as possibly imagined by some commentators. Limited studies in DOTS have indicated that errors may be of no greater order than some from other measurement errors. However, these results have not been more formally researched across a number of states.

For some of the research questions addressed in this thesis, it was possible to make more definite or at the least, tentative LRS field operation recommendations on the basis of research carried out in this thesis. On these particular topics, at least some further research is required. For example, within current frames for undertaking LRS:

1. **Mileage Equations**: On their use, it was possible to state that their use was in general not recommended (as reviewed in Chapter/section 6.7). However, this needs to be further verified and checked.

2. **Length of Routes**: This is an example of a topic that were not explicitly covered in the Case Study questions. It is however possible however on the basis of the research carried out here and elsewhere to make general recommendations. As reviewed in Chapter/section 10.7.3, longer routes are often to be preferred form a purely data management perspective. This topic however ideally needs to be further analyzed on a more rigorous and detailed basis.

3. **Mileage posts**: A more tentative recommendation is that the use of these would seem to be lessened (see Chapter/section 6.6). However, this should be further researched. It was deemed likely from research carried out here, that the cost of accurately maintaining mileage posts was potentially likley to be a critical factor in their demise in the next 10 years after 2000 years or more of their use. However, this topic could probably benefit from some more formal research as:
   a) Many DOT’s have large existing legacy investments in MP, and,
   b) Research may indicate there are other possible benefits to keep them in use (e.g., for driver information), or to at least to
maintain them at some minimal level (but a level that needs to be defined).

Other more detailed topics for further research other than those outlined here are included in the Conclusions of each Chapter.

10.6.3 New Conceptual Frameworks for LRS

Appendix G reviews in outline a proposed new conceptual framework for LRS. A number of items for further research became apparent from this exercise undertaken in that Appendix. Ten topics for useful research in this area include:

1. **Highway Elements:** The research would further develop and define a “transportation Lego”. There is a need to better identify and more fully define a standard set of highway elements (i.e., network objects), including intersections (i.e., from simple to complex cloverleaf), and associated highway elements (e.g., truck run-offs, rest stops, etc.) for possible encoding within a standard highway object classification schema.

2. **Route Hierarchy:** Further justify the use, develop the technical basis for and test application of the route hierarchies (e.g., segment, link, route, super route, etc.) identified in that appendix. In particular, determine which hierarchies there is a clear transportation field justification for and others which none is known to exist.

3. **Network Object:** Further develop and evaluate the properties and behaviors to be most usefully associated with these objects. These should include topological, geometric and database properties.

4. **Inheritance:** Evaluate the way properties and behaviors may be passed from network to route to link, etc.

5. **Time:** A detailed study is required to more precisely tie down and evaluate all the ways time is used in association with networks and LRS. Chapter 7 provided a reasonable list of the required time functionality. However, these items need to be teased out not just at the “paragraph level”, but at the “chapter level”. Clearly, the more detailed study of time management on networks and network-based attributes could be a further very useful thesis or two in their own right.

6. **Conceptual Data Model:** More fully develop the outline conceptual data model provided in Appendix G. This would include a careful consideration of the “composition” relationships.

7. **Object Pattern:** These may provide a way of creating very generic network-based units that can be used across multiple transportation applications. Their use needs to be further investigated.

8. **Test Case Study Application:** This exercise would build a detailed model of the proposed schema and evaluate it use in a number of different uses and applications including uses across different transportation modes.
9. Other Network Applications: This research would evaluate the objects created for transportation use and how they compare to the need for objects in other network-based applications (e.g., utilities, such as transmission lines, for gas and electric lines, etc).

10. Comparison to Existing Road Data Model Frameworks: The above conceptual schema as further developed, should be compared and contrasted in detail to the existing LRS data models in use (e.g., the NHCRP 20-27(2) model).

10.6.4 Further Research Summary:

The above two five-part lists (of both higher-level and more technically focused LRS research questions), and the addition of the new conceptual framework for LRS, are by no means exhaustive lists for further research in LRS. However, they do provide indication of:

1. Research Richness of LRS: The fact that LRS in general is a rich area for research, reflecting the fact that the one-dimensional case has previously been largely ignored (as reviewed in Chapter/section 1.2.4).
2. Priorities: What at least in view of the work carried out here are the main areas and possible priorities for further research.

10.7 Summary Identification Of The Contribution Of This Thesis

This thesis attempted to make a contribution in the following terms:

1. Methodological
2. Theoretical
3. Planning Practice

In final conclusion, the following sections give a brief summary of the identified potential contributions from this thesis.

10.7.1 Methodological:

The research methodology used here was a multi-faceted, layered, iterative approach. This would seem an approach appropriate to use in many planning research efforts. In reality, many planning research efforts utilize just one research approach (for example, “Case Studies”). Research form should follow research function. The research carried out here simply indicated that more holistic multi-faceted approaches are appropriate for tackling the multi-faceted type of planning problems examined here. A reliance for example on the state DOT case studies for LRS alone would have been given at the very least, partial, more likely erroneous, results in this research activity. As example justification, it was found in the course of this research that most of the expertise in LRS does not reside in DOTs, but in the outside consultant communities.

Notwithstanding the above observations, it may be noted on the development and the use of multi-faceted, layered, iterative research methodology (RM) approaches:

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1. **RM Development**: Have not been previously clearly drawn out in the planning information systems literature, at least that examined and referenced for this thesis.

2. **RM Use**: Provides a useful ‘critique point’ for much of the existing research work carried out to date in the planning information systems field (and even in parallel fields, such as engineering systems analysis).

The core of the research method developed here could be further developed and adapted and used for other network spatial “messy” problems (such research on *Network Conflation* and *Network Generalization*), as well as other spatial messy problems (such as any type of spatial conflation, or the wider development of spatial data and spatial data processing standards, e.g., such as for meta data). The basic but key, over-riding theme on all these research topics is that their the research approach has to attempt be both broad and sensitive to all relevant design elements to craft solutions that may be meaningful to field practitioners.

### 10.7.2 Theoretical

#### 10.7.2.1 LRS Context

This thesis has critically attempted to “frame” LRS practices and the wider body of adjoining literature to the field of LRS. It was argued that there has relatively little published directly on the wider consideration of LRS itself to date. The two partial exceptions to this are:

1. **Individual DOT Coding Efforts**: These are typically DOT “operational” papers. These are largely focused on the coding details of their particular LRS. (Many of these are contained on the BTS CD-ROM, reviewed in Chapter 4. See also the literature examples from the Iowa, Minnesota, and Idaho DOTs).

2. **Data Models**: These contain details of the LRS data models (as reviewed in Chapter 5)

There has been virtually nothing published which has attempted to place a higher level frame of analysis on the wider set of LRS uses, practices and theory. This thesis has attempted to critically fill this gap.

There have been a number of commonly held basic conceptual misconceptions with LRS, both in the field and with academicians in LRS. (Some of these misconceptions became evident in the Expert Panels that were conducted). Two common central misconceptions were in short:

1. **Role of LRS**: “It is a narrowly-based measurement science”, or alternatively expressed, “It is a focused sub-area of Surveying”.

2. **Complexity of LRS**: “It is a fairly simple topic”.

This thesis has demonstrated in short that these views are at least partial if not clearly inappropriate. In summary, there are two main reasons for this:

1. **Role of LRS**: The activity as carried out in the field is focused and concerned with data management and planning type analysis. It does have a methodological relationship and basis common to “Engineering Stationing”, but a different end
goal. For practical end purposes, LRS is essentially used to support data management. Engineering Stationing is undertaken to support design and construction activities (as described in Chapter 3). LRS as reviewed in this thesis is thus practically (at least today) more related to the fields of Planning and Information Technology. This distinction again while a fairly basic one, runs counter to the prevailing common sense of the “epistemology” for LRS. Such revised consideration may best assist the further practical and appropriate field development of LRS theory and practice.

2. Complexity of LRS: While the document produced here has a certain breadth and depth, it has tackled one set of the more common field circumstances and issues that occur with the set-up and utilization of LRS. In many areas, the top ten example issues or topics were addressed. The work thus indicates that LRS is a much richer topic than an initial examination might give indication. The basic LRS model is simple. However, the application of that model to real world circumstances and detail is what becomes complicated. It is argued above that as the complications are multi-faceted, planning is a discipline that has a track record of tackling such problems (especially in the spatial domain).

Placing a consideration of LRS in the appropriate domains was one contribution to the further theoretical development of the field.

10.7.2.2 GPS and LRS

Another conceptual contribution of this work was the furtherance of the concept of LRS as a way of abstracting a “useable level” of information from more detailed spatial data sources (such as generated by a GPS-equipped highway data collection vans).

The LRS schema is viewed as a way of providing a database spatial location metric measurement schema where ambiguity might otherwise exist. Computers can calculate solutions where complexity does not exist, but cannot do so readily where complexity does exist (for example, it is not clear whether the data observation near a road intersection is for road A or road B).

This idea is a little more further described in Chapter/section 10.4.2 and 10.4.4.

10.7.2.3 Highway Data Objects

One of the most significant single ideas promulgated in this thesis was the set-up of highway data objects that can be more readily managed from the purpose of both attributes and spatial coordinates. Currently, DOTs already typically manage highway data attributes from predefined highway data sections. As reviewed in Chapter 4, these are typically called “control sections”, and in some DOTs have been in place since the 1950’s. Thus, on the attribute data side the use of highway data objects as a concept already occurs.

The corresponding development of a toolbox of highway spatial or geographic “parts” has not occurred to date. This may be viewed as, “a transportation spatial network Lego” or TRANSPORTATION LEGO, as laid out in Chapter/section 10.5.

Table 1 of this thesis laid out some of these basic network forms. The set-up and management of transportation networks has typically proved a very time-consuming task within DOT’s, at a
period when staff resources to complete such tasks have been very limited. The set-up of even the 1:24,000 base year transportation network within a state DOT has typically been a multi-year task. In terms of spatial encoding, DOTs to date have tended to use the spatial object forms provided by COTs GIS vendors. These forms have not necessarily been well-adapted to the operational working activities of transportation agencies.

10.7.2.4 O/RDBMS and Place of Highway Objects

Lastly, on the basis of the work carried out in this thesis, in very much related fashion, it is further proposed that there is a user-defined need to give a greater emphasis to managing the above network spatial objects as the primary data storage entities. This is in contrast to current day COTS GIS. These COTS have a first emphasis on “managing the geography” (i.e., the spatial coordinates), and, then, creating or associating higher-order spatial objects (such as highway spatial objects) from the underlying spatial data sets. The ‘highway data object first’ (or, logical versus the geographical network) approach is proposed in short given the following factors:

1. **Route Identifier Constancy**: Route 30 as an object that is managed may potentially stay more fixed over time (say 50 years), than the coordinates (which say change with current technology on the basis of say even monthly data collection exercises).

2. **Need for Representational Flexibility**: The widely varying levels of network spatial development (in terms of spatial features and accuracy, etc.) of different transportation agencies.

3. **Network Spatial Diversity**: Different levels of development of even one single network at different times. For example, parts of the network may be at 1:24,000 scale, parts at 1:12,000, and other parts at “unknown digitizer scale”.

4. **Multiple Coordinate Sets**: Most importantly, it is quite common existent practice, already, to need to maintain different sets of spatial coordinates for networks (for example, representing, different data collection exercises, official “log” views, and for different representational needs).

Further research should further identify and define these highway forms and their key characteristics and behaviors. Certainly, this thesis was first a study on LRS. The above operational requirements have been fairly clearly delineated and justified in this thesis from a LRS perspective. However, the detailed operational working of such schema needs to be best further developed and “operationalized”, as indicated above, taking account of also still wider transportation analytical network needs (for example, for transportation network flow analysis, ITS community needs, etc.).

Thus, the synthesis of the proposed development in practice is to managing first, “the data management object”, rather than, “the geography”. In short, the geography or coordinates becomes a property of the data management object. This notion is somewhat contrary to much existing GIS field practice at least to date.

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10.7.3 Planning Practice

This thesis has argued that judging from the typical uses reviewed, LRS may be best first viewed as “Planning Information Systems”, rather than an “Engineering Information System” or an engineering data system (see Chapter/section 9.2.2). This thesis has thus attempted to make a practical contribution to the development of LRS practice in this light.

A foundational business system to a DOT may be defined as a fundamental system component to many core management systems (e.g., pavement management, congestion management, etc.). In particular, it may also be a fundamental tool or “key” for the creation of agency-wide transportation data warehouses. (The Maine DOT Data Warehouse effort was essentially an effort in developing and applying enterprise linear referencing systems).

In these IT development terms, it may be argued that the setup and institutionalization LRS is a foundational business system for DOTs. It is thus appropriate that accepted IT “best practices” be utilized in its development and set-up. The Zachman Framework was identified as a “best practices” approach to IT development. In Chapter 9, the Zachman Framework was largely reviewed in terms of the framework acting as a mechanism for including institutional concerns. However, in a larger sense, the Zachman framework is more widely recognized as a comprehensive framework for best practice IT development. It is thus appropriate to consider LRS development in this sense. It is not attempted here to fully instantiate the Framework for LRS. However, many of the necessary data items have been identified in this thesis. The following figure provides an example top-level summary of some key contributions that have been made to planning practice in this thesis within the analysis structure of the Zachman framework.

Only key contributions of planning practice are identified above. Further research might further detail develop and instantiate the use of this framework for LRS.

In terms of contributions to the Planning field use of LRS this thesis has identified a number of technical areas where detailed recommendations to procedures have been made. These are not fully re-iterated here. All of these assume the operation of LRS within existing schemas (the adoption of a new Lego schema within the previous section would require further detailed review of these). They included (here, without full supporting details), for example the following five:

1. **Mileage Equations**: The dropping of the use of mileage equations is proposed. Chapter/section 6.6 of the thesis deals with mileage equations. They were originally introduced 50 years ago as one response to deal with the issue of Geometric Update. They are now recommended to be dropped because of the practical difficulty of maintaining them, the difficulties in particular of maintaining them when routes are extended, and because database-level routines are not available that offer more automated ways of dealing with Geometric Update.
Table 61  Zachman Framework: Summary Planning Practice LRS Contributions

<table>
<thead>
<tr>
<th>DATA</th>
<th>BUSINESS PROCESSES</th>
<th>TIME</th>
</tr>
</thead>
<tbody>
<tr>
<td>LRS mainly deal with planning-level data.</td>
<td>Standard processes need to be defined for data collection, including with use of GPS</td>
<td>At current period, annual cycle of updates and comparisons a key need, not necessarily more regular temporal ones</td>
</tr>
<tr>
<td>Concerns with accuracy only within working “context” of application requirements</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>TECHNOLOGY</th>
<th>INSTITUTIONAL FACTORS</th>
<th>MOTIVATION</th>
</tr>
</thead>
<tbody>
<tr>
<td>Suggest adoption of LRS standards and technology (such as the transportation Lego, earlier proposed)</td>
<td>Key implementation issue for LRS; LRS typically needs to be considered as part of wider GIS implementation effort which it is part of</td>
<td>LRS mainly driven by needs of the core DOT (former ISTEA) management systems</td>
</tr>
</tbody>
</table>
2. **Traversal Lengths:** Use of longer data storage traversals, rather than shorter, is proposed. While in theory the creation of “SuperRoutes” (say, state level) from lower order route elements (say, county level) is straightforward, in field reality this has often proved more a little more practically difficult than it might conceptually appear (for example, because of coding differences that crop up with time). It may also create breaks in data management objects that might not otherwise occur (e.g., nothing changes in Interstate 80 as one passes from Sussex county to Essex county).

In determining the which lengths to use with LRS, usually *local administrative and other operational reasons* will dictate these. However, where freedom exists to recast the route system, there may be advantages to going to a route system with a *lesser number of longer routes*. Considering the State of Vermont example, a smaller state, it was deemed to be advantageous to at least data manage state maintained roads on a *state line-to-state line route basis*, rather than maintaining and managing a greater number of *county-line to county-line* based routes. (One simple advantage was that the there was a user need to report state-level based route data to meet federal reporting requirements. While the translation from county to state-based routes was in theory easy, in time, the process became broken and messy to maintain). If data collection methods could determine **TRANSPORTATION LEGO transition points**, long traversals could be easily implemented.

3. **Mileposts:** It is proposed to reduce the support for the maintenance of mileposts: In short, the advent of cheap wearable GPS devices may in part reduce some of the justification for mileposts (if not totally reducing the justification).

4. **Traversal Identifiers:** It is proposed to use independent identifiers with highway storage elements. The use of random independent identifiers is preferred from a strict database management science perspective; however, the use of others ID’s (such as highway names) has also been found to work reasonably well in the field. (see Chapter/section 6.3).

5. **Anchor Nodes:** The adoption of the anchor node and anchor section schema was supported. This schema was as proposed by Joe Ferreira and adopted as a center point of the NHCRP 20-27(2) model. This thesis has proposed the use of the objects on an incremental, accuracy-improving basis (see Chapter/Section 10.5.2).

The fuller development of the approaches indicated here would potentially enable networks to gain a higher degree of knowledge of topological, geometric and attribute “intelligence”. This would be useful not only to assist with the encoding and placement of LRS schemas, but the fuller development of *the intelligent network*. Such a network would potentially be able to “generalize”, “conflate” and re-linearly references itself, if not in real time, at least in reasonable “analysis time”, at least for the size of data sets commonly used in DOTs today and likely to be used in the near future.

Such *“smart networks”* would of course potentially have significant additional data processing overheads associated with them. However, for the bulk of the DOT applications
reviewed here (compared to ITS and transit needs) processing in real time is not the issue, while lack of staff resources to clean networks (with appropriate methods and tools) very much is a practical concern. Much faster processors and smarter processing techniques potentially justify the further development of such approaches in the years to come.

The methodological, theoretical and field practice developments proposed in the body of this thesis stand in their own right and it is hoped act as immediate potential field contributions. It would additionally appear that in the longer-term these proposals are also one-step in the longer-term development of representations of intelligent (or, "smart") transportation spatial networks.

10.8 Final Conclusions

10.8.1 Progress Achieved

This thesis has attempted to put a research foundation under LRS related research activities by acting as a "bowsprit" research effort in this area. The work here has encompassed many aspects of LRS and areas of direct relation. By establishing such ontology and epistemology, it is hoped that further research will be able to proceed to core areas with better direction and efficiency.

As noted in Chapter 2.4, there can certain costs in undertaking such type of ground-breaking research (as conducted for this thesis). However, in meeting the needs of practitioner communities, such research is often first called for. This thesis has hopefully created a base from which research efforts on the topics above can best focus with some gathered clarity and reference.

10.8.2 Summary of Field and Design Level View

Linear referencing is well established as the principle means by which transportation agencies manage data related to transportation networks. However, emerging technologies, new methods of data collection (such as GPS) and the changing and expanding responsibilities of transportation agencies have altered the way the linear referencing is viewed, and, potentially implemented. Linear referencing is now viewed as just one type of location referencing within a larger location referencing system. The implementation of linear referencing in GIS has become the norm. The full integration between linear referencing control databases and GIS has become desirable as the display and analysis of current and historical information moves from wishful thinking to a practical reality.

The design and refinement of LRSs will continue with greater sophistication to meet new objectives. Greater data integration will enable more thorough analyses to improve the decision-making process of where to best invest in the transportation network to meet various (often conflicting) needs. Linear referencing methods, as one key component of robust location referencing systems, will provide an essential framework for development of integrating transportation information system (ITIS), intelligent transportation systems (ITS), GIS-T and related endeavors.
LRS may not be the “best way” (e.g., most spatially accurate) of defining location, but it may be the “best way” (e.g., convenience, ease of use, etc.) to manage data that is essentially linear in form.

This thesis has proposed some ways to tune-up existing LRS practices and also a possible new basis for developing LRS (the Transportation LEGO).

10.8.3 Business Process View on LRS and Models

This thesis sought to bring some field-focused balance to work completed to date on LRS. A higher-level conclusion may be reached on the LRS research previously carried out. The previous existing LRS work has produced "strongly typed" data models.

In contrast, this thesis has implicitly promoted extension and reusability for related (transportation network-based) applications. As described in Chapter 3, LRS ties together a significant proportion of many different data sets in a DOT. Thus, the concerns of extension and reusability particularly apply to LRS. Strongly typed models, which neglect effective study and description of the underlying abstract framework, and rely upon discipline specific concepts, may have as at least one major concern -- that is, limited extensibility into other arenas. These other arenas include those that represent other disciplines and business domains, and those that represent more abstract models of knowledge or generalized process. This thesis attempted a more solid base of field observation (such as outlined in particular by the work summarized in Chapter 6).

Such strongly typed models may be considered "resource consumptive". That is, they involve creating information vocabularies, and complete descriptive structures must also be implemented to support them. Chapter 3 of this thesis reviewed the different domains with an interest in spatial networks. The previous model approach curtails cross-discipline information exchange and can act to limit the possibility of more generalized cross-fertilization of knowledge streams.

The "business object" model as a standalone model is largely a "quick and dirty" way to tackle the issue of process description with in-depth understanding of the more general aspects of the process. Without establishing an abstract context, these models become "dead-end" because they fail to support new linkages and fusion of knowledge areas. In many ways, this is contradictory to the evolution of conceptual representation, and in particular, the wider development of object oriented models and concepts. Through the general properties of objects, "reality" is represented through a single hierarchy of derivation and inheritance. In the best instantiation of the approach, new objects to represent derivative trees within the hierarchy are created begrudgingly because each new object detracts from reusability. This builds on the basic axiom that the greatest facilitator of knowledge development is establishing "linkage" (and composition). This is sometimes called the, "the ah-ha experience". Such experience was noted in this thesis in reviewing the "network games" practitioners played in the different transportation information communities. While the ordering and assemblage of network components on which to base LRS was different, they typically exhibited a similar high-intermediate-lower order of objects worked with. They in fact exhibited the properties of an "object pattern". (Martin, at al, 1997).

Today, it seems like the "economic model" and the "knowledge development model" are at cross-purposes. A pure market driven economy requires rapid response to competition or impending competition. This in turn drives a pragmatic, short-term approach to implementation and development of knowledge to support implementation. The "immediately useful" takes
precedence over stronger and more robust structure development. As the lines separating institutional actors continue to blur, so do the value systems and the differentiators between markets and competitions (for example, MIT ends up competing with the Ford Motor Company). As this happens, the ability to develop knowledge based on different success criteria erodes. In the end, analysis frameworks, practitioner work and thence ultimately society gets dominated by short-range considerations. The shift of responsibility for matters like LRS standards from a model of pro-active planning by the research community to the de facto domination by commercial suppliers (such as COTS GIS) illustrates this.

At the highest level of academia and “reflective practitioenering”, it should be asked, "can anything disrupt this general trend?" In essence, in a world dominated by consumptive social and political instincts, is there any vehicle to curb those instincts and to readdress issues of sustainable social progress (and improved practitioner arts)? Maybe there is. In social ecology terms (Light, 1998), there are two basic frameworks to direct activity. One is “mechanical” (this is, for example dominated by hierarchies). The other is “organic” (that is, less structured). The issue is ultimately that of control. Control is achieved by dominating key routes through any network (social, physical). Systems that are organic operate on an interaction and propagation model and carry the benefits and drawbacks of true organic systems. They adapt rapidly. They can propagate both good and bad influences through cellular inheritance (for example, “the Melissa virus”). The internet (which is now so central to the hierarchical and short-term oriented culture) is it's greatest weakness because of how it mimics organic systems and limits domination of specific influences.

The importance of this in the LRS model context is that potentially the internet is the forum for an alternative to the dominant cultural metaphor. It provides the opportunity to develop and promote other (application development) metaphors. As such, it can undermine the loss of robust abstract foundations (married with firm field understandings) for the development of practical concepts.

What one is addressing in the context of LRS models may in some sense be regarded as an example of the tip of a wider field practitioner, and still wider yet, “cultural iceberg”. The current trend in most areas is to limit access to knowledge to the local task oriented requirements. Even knowledge which could be provided as supplemental is either "drill down" or hidden to eliminate confusing (or informing?) the user. Now, recently, there are new products which filter the desktop to provide an even more limited perspective. This is done in the name of "making it easier to operate in an increasingly technologically sophisticated world". But as the recent “Melissa Bug” shows, also to channel and caste people into groups which can perform specific functions and tasks without challenging their purpose. As end-user knowledge decreases and dependency grows, hierarchical control becomes stronger.

In several areas, this thesis challenged some of the “conventional wisdom” surrounding LRS. Some of this conventional wisdom has been quite resolutely held. It has been argued on the basis of the research carried out here they these wisdoms are in fact often largely misconceptions. They include the following three examples:

1. “GPS will do away with LRS”. This thesis argued that LRS has certain intrinsic advantages from a technical viewpoint which justify not only its retention, but it’s expansion, enhancement and delivery. In addition, the advent of GPS equipped vans to collect highway data is producing large volumes of linear/traversal form encoded highway event data.
2. "The LRS uses should be highly concerned with data accuracy issues and more accurate spatial data". This thesis argued that a transportation user-focused analysis indicates that many LRS uses are actually "planning level" focused. Different spatial coordinate data sets may be maintained for different purposes.

3. "What the LRS community needs is a data model we can all use". This thesis argued that a single data model is unlikely to meet the wider set of needs of the wider set of transportation communities, and instead a "LRS toolbox" approach is proposed.

In simpler terms, challenging the knowledge models that are evolving around matters such as LRS is, in essence, challenging a mechanically and hierarchically driven society that seems to always veer to accepting over-simple models of reality.

The world may be regarded as a lot more complex today than that of Roman times, but, it is also, to be true, unchanging. The soldier on Hadrian's Wall had a primal need to know how far he was from Rome. Today, we all still need to know how far we are from home, even if the variety of ways and means for reaching home have expanded.

Figure 76 Miles from Home

"All roads do not lead to Rome."
10.9 Chapter References


APPENDICES
APPENDIX A: GLOSSARY

This Glossary defines in a little more detail some of the key terms used in this thesis. Some alternative definitions are provided to assist the reader of other publications on linear referencing.

Many of the definitions refer to ‘roadways’ for convenience. The reader should be aware that linear referencing is not confined to roadways, but may be applied equally well to other Travelways (railways, waterways, airways), utility lines, or other linear features.

The definitions in this glossary are derived from the following sources. In some cases, the definitions provided are slightly modified or simplified from the original version, so the original source should be referred to for definitive definitions. Definitions without a citation are based on common usage or compiled from a combination of sources. Those sources included:


Anchor point. A zero-dimensional location that can be uniquely identified in the real world in such a way that its position can be determined and recovered in the field. Each anchor point has a 'location description' attribute that provides the information necessary for determining and recovering the anchor point’s position in the field. Location descriptions can vary and can be quantitative, descriptive or both. An example would be the intersection of the centerlines of Oak and Maple Streets.

Anchor points can be understood as 1-dimensional control points, in that they serve the same purpose as geodetic control points in 2 and 3 dimensions (i.e., they are the fundamental objects to which all other objects are directly or indirectly tied) [3].

Anchor section. A continuous, directed, non-branching linear feature, connecting two anchor points, whose real-world length can be determined in the field. Anchor sections are directed by specifying a 'from' anchor point and a 'to' anchor point. Anchor sections have a 'distance' attribute that is the length of the anchor section measured on the ground. Anchor sections provide the fundamental referencing space. The collection of anchor sections in a given linear referencing system is analogous to the ellipsoid surface in a geodetic datum or the map projection surface in a 2-dimensional Cartesian referencing system [3].

Cartographic Representation. A set of lines that can be mapped to the linear datum.

Control point. A point at a node along a given traversal with a known linear measure. Control points are generally used to calibrate the linear measures along traversals. The term is sometimes used synonymously with reference point.

Control section. A general (and ambiguous) term for a section of roadway, with well-defined end points and a known length. Control sections may be established based on consistent linear attributes (pavement type, number of lanes, etc.), but this is not required.

Dynamic segmentation. The geographic overlay and display of attributes associated with traversals, describing events (features or characteristics) along a linearly referenced network.

Event. A feature, characteristic or phenomenon that occurs along a roadway (or traversal) and is described by attributes stored in a database, including its location specified by a linear referencing method. See point event, linear event.

Line. A generic term for a one-dimensional object" (SDTS, 1992). A line can be a line segment, a string, an arc, or a chain.

Linear event. A 1-dimensional event with location specified by a two linear measures along a traversal. A linear event must reference one ‘start’ and one ‘end’ reference point along the same traversal. See event.

Linear measure. Another term commonly used for ‘traversal measure’. See traversal measure.

Linear referencing method. Simply, a mechanism for stating the location of an unknown point along a network by referencing it to a known point. A location referencing method in which a location is specified as occurring on a uniquely identified linear feature (i.e., a traversal or link), at a set distance and direction from another point with a known linear measure (often the beginning of the traversal or link). See location referencing method.
Linear referencing system. A location referencing system (defined below) comprised of one or more linear referencing methods. See location referencing system. Policies, records, objects, and procedures that relate the included linear referencing methods.

Link. A topological connection between two ordered nodes. A 1-dimensional object that is a topological connection between two nodes [2]. In common parlance, the term ‘link’ often refers as well to the linear feature that connects two nodes in a GIS centerline layer. However, a clear distinction is made for data modeling, where a ‘link’ is simply a topological connection, and a ‘line’ has shape and position and can be used for cartographic representation.

Location referencing method (LRM). The technique used to identify a specific point or segment of a roadway, either in the field or in the office [1]. As cited in [2], a linear referencing method is composed of at least one traversal and at least one traversal reference point. See traversal, traversal reference point.

Location referencing system (LRS). The total set of procedures for determining and retaining a record of specific points along a roadway. The system includes the location referencing method(s) together with the procedures for storing, maintaining, and retrieving location information about points and segments on the roadways [1].

Mileage equation. A formula used to equate two linear measures at the same point along a traversal. For example, “2.06 miles back = 2.08 miles ahead.” Mileage equations are used when a realignment or re-measurement has occurred, so that ‘downstream’ measures do not need to be adjusted. When used, the linear measures are discontinuous and may not represent true accumulated mileage along the traversal.

Milepoint. The mileage displacement from a beginning of a linear feature to any location along the linear feature [1].

Milepost. A physical entity, ordinarily a sign, placed beside a roadway and containing a number that indicates the mileage to that point from some zero point on the roadway [1].

Network. A graph without two-dimensional objects or chains.

Node. A zero-dimensional object that is a topological junction between two or more links, or an end point of a link [3, simplified].

Offset. A distance along a traversal from a point with a known linear measure (a traversal reference point). A ‘milepoint’ generally refers to an offset from the beginning of the traversal.

Point event. A zero-dimensional event with location specified by a single linear measure along a traversal. A point event must reference one and only one traversal reference point. See event. It is described in terms of its attributes in the extended database.

Ramp. A connecting roadway between a freeway or expressway and another highway, road or roadside area.

Reference point. A fixed, identifiable feature, such as a signpost, intersection, or bridge endpoint, from which a location can be measured or referenced [1]. Reference points with known linear measures (e.g., milepoints) can often be used to calibration the linear measures along traversals in a GIS, depending on the GIS software.

Reference post. A physical entity, ordinarily a sign, placed beside a roadway and containing a number that identifies the location of the post. The identification number is generally associated with the actual milepoint of the location in office records.

Route. An ambiguous term which is often used to mean (a) a numbered or named highway (or roadway) as signed in the field, (b) a traversal with associated linear measures, or (c) both of these. See traversal.
**Section.** An ambiguous term that generally refers to a section of roadway between major roadway features (e.g., intersections). In the context of dynamic segmentation in GIS, a traversal may be comprised of sections, each of which corresponds to one link or a portion of a link, directed along the link with specified from and to measures.

**Segment.** An ambiguous term referring to any portion of a roadway. In the context of dynamic segmentation, a segment is a length of roadway between two specified milepoints.

**Travelway.** A roadway, railway, waterway or airway.

**Traversal.** An ordered and directed, but not necessarily connected, set of links. Coding conventions are required for establishing traversal directionality and for specifying non-connected traversals [2]. The original definition in [2] specified a “set of whole links”, however the term is used slightly more generally here in that a traversal is not constrained to whole links (as is the case for common GIS software). Note that the direction of a traversal along any link may be concurrent or contrary to the direction of the link.

**Traversal measure.** See traversal reference point.

**Traversal reference point.** A zero-dimensional location along a single traversal that is used to reference events along the traversal. Each traversal reference point has a ‘traversal measure’ attribute which is used to locate it along the traversal. ‘Traversal measure’ is an offset measured from the initial node in the traversal to the traversal reference point [3, simplified]. See Reference Point.
APPENDIX B: SHORT ANNOTATED LRS BIBIOGRAPHY


This relatively early synthesis of location referencing methods, by Blessing and Blake, provided an overview and framework of existing practices along with definitions, which continue to be used today (e.g., the distinction between linear referencing methods and linear referencing systems). (23 pp. plus appendices.)


Problems and solutions of combining different linear networks through conflation are discussed, including the resolution of one-to-many and many-to-one relationships between linear elements, route systems, left-right oriented attributes, etc.


A number of concepts and ideas are compiled on how a state transportation agency could use an enterprise data model to implement a GIS for Transportation (GIS-T), including the enhanced integration of ISTEA management systems. A high-level GIS data model is presented, including the elements of a linear referencing system, and implementation choices are discussed. Appendices address using road names as external identifiers, relevant relational database design principles and the Transfer Standard. Available at http://www.upa.pdx.edu/CUS/. (17 pp. plus appendices.)


Describes the general concepts of linear referencing and the application of dynamic segmentation as a means of storing location information.


This report presents a summary of Federal agency needs for ground transportation networks, as an initial step toward the development of an overall requirements document for spatial data related to ground transportation. Requirements described in the report are limited, as they are based on responses of just 11 FGDC Ground Transportation Subcommittee members to a questionnaire. (21 pp.)


The FGDC Ground Transportation Subcommittee recommends that (1) a standard linear LRS be included as part of any transportation network profile established under the Spatial Data Transfer Standard, and (2) that any transportation network databases developed as part of the National Spatial Data Infrastructure include, as part of their core data, all key linear LRS
attribute fields. Recommendations are also given for railway and waterway linear LRSs. (8 pp.)


Federal HPMS submission requirements include incorporation of a linear LRS for all rural arterial, urban principal arterial and National Highway System (NHS) segments included in the HPMS database. One essential requirement of the linear LRS is that any route/milepoint must specify a single, unambiguous location.


The summary report for the phase of the GIS-T PFS which developed the Linear Referencing Engine.


This document reviews and evaluates Linear Reference Methods and associated implementation issues.


This document describes the ‘dynamic segmentation’ model for implementing linear LRSs with GIS, and includes case studies from the Pennsylvania DOT and the Vermont Agency of Transportation.


The objective of this study was to evaluate the feasibility of utilizing an object-oriented data model for GIS-T, including analysis of LRS-related issues. The Task 1 report includes an annotated literature review, addressing GIS-T standards, data management issues and current GIS-T research initiatives. (63 pp. plus appendices.)


This report analyzes several problems and issues encountered in GIS-T network analysis (and identified in the Task 1 Report), including network definition, linear referencing methods and network conflation. A summary of the Pooled Fund Study Linear Reference Engine (LRE) is provided. In brief, the LRE is a proof-of-concept model for converting location specifications between different linear referencing methods and a datum (i.e., a reference network). The report also evaluates options for development of an object oriented GIS-T data model. (67 pp.)


This report applies the findings of the Task 1 and Task 2 reports from a business perspective, defining strategies for product development, and reviewing market demand and product development cost considerations. (12 pp.)

Provides an overview of key issues related to location referencing for intelligent transportation systems. The material summarizes work to date performed by ORNL, as tasked by the FHWA, to develop consensus positions on spatial database issues. The paper presents a practical approach to standardization.


The ITS community has indicated a need for development of a common location referencing method to cover a majority of ITS applications. This paper discusses interoperability requirements for ITS, critiques the "common method" approach, and recommends that multiple location referencing standards be developed and specified within an interoperability protocol framework, the Location Reference Message Protocol.


A preliminary specification is provided for the Location Reference Message Protocol (LRMP), an interoperability protocol for message formats for communication location reference information for ITS applications.


Presents a general, feature-based data model supporting linear referencing dynamic segmentation, avoiding undesired link segmentation.


A brief overview of the capabilities and uses of MGE's segment manager is provided. Available at http://205.139.151.5/iss/industries/transportation/papers/mgsmswp.htm. (7 pp.)


This report aimed to help Mn/DOT standardize on a limited set of location reference systems, including two linear LRSs. (31 pp. plus appendices.)


This report contains the findings of a Location Data Server Task Force, whose mission was to examine the feasibility of developing a location translation server for performing translations between different location referencing methods. Recommendations were made for development of applications and data for translating between different location referencing methods, and for establishing the responsibility for development and maintenance of the applications and associated databases. (About 100 pp.)


Data model structure issues for linear LRSs are discussed, including many literature references. A suggested terminology is given for linear LRSs and LDMs, and a framework (made up of largely key questions) is provided for evaluating linear LRSs and LDMs. Entity-relationship diagrams are presented for several optional data model structures.


This paper discusses five location referencing methods and strategies for their implementation, then examines components common to the methods and discusses how they form the basis of a set of standards for a location referencing system for ITS user services. The system permits multiple location referencing methods and coding schemes to operate within a single framework. (16 pp.)


Describes use of an ArcView application for translating between different referencing methods for the Utah Department of Transportation. Available at http://www.esri.com/base/common/userconf/archive.html.


Information strategy planning efforts at the Wisconsin DOT are described, with emphasis on Location Control Management, a business area identified as needing further analysis in their Information Strategy Plan of 1991. The paper concludes that location has three logically interdependent levels: Geodetic, Geographic and Linear, and proposes that implementing these levels will allow more flexibility in managing location for meeting their business needs. In particular, a link-node LRS is proposed as a potential neutral LRS which could be developed and used for translating between other LRSs already in use. (19 pp.)


Describes, in general terms, ITD’s linear referencing system, which includes management of historical data by date stamping location references.


A detailed location data model is described and presented as a series of entity-relationship diagrams. The process for developing the data model is also described. (23 pp. plus appendices.)

This paper details work performed for the Minnesota DOT to determine a standard linear referencing scheme, with the ultimate goal of arriving at a unified definition of location. Although a simplified definition of location was achieved, the paper explains why a single definition of location was not possible. Road segments were defined as viewed by different data users, including ‘simple’, ‘directed’, ‘detached’, ‘laned’, and ‘component’ road segments. A comprehensive linear LRS bibliography is included. (22 pp.)


This working paper describes the ITS datum, a set of nodes and links which all ITS users would have available as a standard non-planar network for referencing purposes. Associated file formats are described.


This paper provides examples of network pathologies, or situations where the network feature is difficult to represent in the GIS due to topology and/or connectivity constraints. (31 pp.)


Includes standardized terminology for linear features in a GIS network.


This paper is a second and final draft report on the above-named workshop. See the final report in Vonderohe et al (1997), below, which includes some revisions to the consensus data model. (34 pp.)


This paper is the final report on the above-named workshop. A consensus location referencing data model is described, which resulted from a workshop attended by 42 transportation professionals in August, 1994. The data model, in object modeling form, associated transportation data with multiple cartographic representations and network models through a single linear datum. Issues where consensus was reached are described, as well as remaining significant points of contention. Supported by the NCHRP Project 20-27(2). (24 pp.)


Findings of NCHRP Project 20-27, including recommendations that transportation agencies develop conceptual organizing principles founded upon the notion of location as a data integrator.

This final report proposes a methodology for design of a linear LRS that will meet specific accuracy requirements. The methodology was developed from geodetic engineering principles and techniques used for designing geodetic control networks. A complete mathematical development is provided founded upon the law of propagation of random error and the statistical analyses of systems of redundant measurements. (83 pp.)
APPENDIX C: GENERAL BIBLIOGRAPHY

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APPENDIX D: NETWORK STATISTICS

Many statistics are used for the analysis of points and polygons. As reviewed in Chapters 1 and 3, even though Network Statistics (in a transportation sense) are given much less attention, they can often be quite important when characterizing a single network (or, sub-network) or when comparing networks. In particular, as reviewed in this thesis, Network Statistics may be useful in:

1. **Network Segmentation:** Helping generate information that can be used to segment a network (for example, into the “Lego pieces” reviewed in Chapter 10 of this thesis)
2. **Network Data Maintenance:** Providing information that may be useful with various checks that may be devised to ensure data quality.

Network Indices may be used for example for:

1. Network size
2. Connectivity
3. Compactness

The following slides provide some examples of such statistics.

**Drawn from:**
1. *Building the GIS-T Database: An Introduction*, Roger Petzold and Simon Lewis, One-day Pre-Symposium Workshop, AASHTO GIS-T '93, Albuquerque, New Mexico, March 28, 1993 and
2. A one-semester course in GIS-T taught at MIT Autumn 1991 by Professor David Bernstein and Simon Lewis.
The Size Of Things

Given a network with \( n \) nodes how many directed links can there be?

- **Minimum:** \( n - 1 \)
- **Maximum:** \( n \times (n-1) \)

How many undirected links can there be?

- **Minimum:** \( n - 1 \)
- **Maximum:** \( \frac{n \times (n-1)}{2} \)
How many networks can be formed from a network with \( n \) nodes (using undirected links)?

Since each link can be "on" or "off"

\[
\frac{n \times (n-1)}{2}
\]

Examples

\[
\frac{7 \times 6}{2} = 21
\]

\[
2^{21} = 2,097,152 \text{ possibilities}
\]
Appendix D3: Network Statistics:

The Size of Things (cont)

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The Size Of Things (cont.)

Given a network with n nodes and l links how many links can there be in a path?

General path: 1

Elementary path: n-1

Given a network with n nodes, how many links can there be in a tree?

Minimum: 1

Maximum: n-1 (spanning tree)
Network Statistics:

Appendix D4: Intuitive Measures

<table>
<thead>
<tr>
<th>Measure</th>
<th>Uses</th>
</tr>
</thead>
<tbody>
<tr>
<td># of links</td>
<td>Connectivity</td>
</tr>
<tr>
<td>MAX # of links</td>
<td></td>
</tr>
<tr>
<td># of links</td>
<td>Connectivity</td>
</tr>
<tr>
<td># of nodes</td>
<td></td>
</tr>
<tr>
<td>MAX # of links in a shortest path</td>
<td>Compactness</td>
</tr>
<tr>
<td>AVERAGE Valence of all nodes</td>
<td>Connectivity</td>
</tr>
<tr>
<td>AVG # of links in the shortest path from an origin</td>
<td>Accessibility</td>
</tr>
</tbody>
</table>

Of course, almost any attribute (e.g., length) can be used as a weight.
Network Statistics:

Appendix D5: Empirical Measures

**EMPIRICAL MEASURES**

The (S,l) Index:

\[ d_{ij} = \text{number of arcs in the shortest path between } i \text{ and } j \]

\[ D = \text{"longest" shortest path} \]

\[ F_x = \text{number of paths of length } x \]

\[ N = \frac{D}{x=0} f_x \]

\[ U_1 = \frac{1}{N} \int_0^D f_x x \, dx \]

\[ U_2 = \frac{1}{N} \int_0^D f_x x (1 - U_1) \, dx \]

\[ U_3 = \frac{1}{N} \int_0^D f_x x (1 - U_1^2) \, dx \]

\[ S = \frac{U_3}{U_2} \]

\[ l = \frac{U_2}{U_1} \]
Using These Measures

How similar are two networks?

Compare the various measures

How spread out is a network?

The longest shortest path has 3 links. So, this is not compact.

The longest shortest path has 2 links. So, this is compact.

How well connected is a network?

Average valence = 1 link # of links / max # = 5/30 = 1/6. So, this is not well connected.

Average valence = 2 link # of links / max # = 3/3 = 1. So, this is well connected.
APPENDIX E: LRS CASE STUDY QUESTIONNAIRE

Linear Referencing Practitioners Thesis

LINEAR REFERENCING CASE STUDY QUESTIONNAIRE

June 1997

Brief Overview

Provides a brief, introductory overview, highlighting key points of the system and areas of particular interest to the reader. This will likely be completed after compilation of the questionnaire.

1. Persons Interviewed

Record the name and position of each person interviewed. For each person, ask how he/she uses linear referencing, what experience he/she has, who else would be important to talk to about linear referencing, etc.

2. Organizational Information

2.1. What office is responsible for development and maintenance of the agency’s linear referencing systems? Describe its responsibilities.

2.2. What office is responsible for coordinating GIS activities? Describe its responsibilities.

3. Overview of Current Use of Linear Referencing

3.1. Can you name and briefly describe each of the linear referencing systems currently in use in your agency?

Note: it’s important to get the “name” by which each LRS will be referenced. Detailed descriptions come in the next section.

3.2. We’ll go over each of the LRSs in detail, but what are the major issues you face, as a department, with regard to linear referencing?

For example: managing updates to the LRS and historical data, integration of data using different LRSs, integration with GPS and other data types, implementation in GIS, development of referencing systems for local roads, etc.

3.3. What formal process, if any, was used for development of your linear referencing system(s), e.g., Information Engineering?

3.4. Describe any current initiatives you have for revising / expanding your linear (and location) referencing.

3.5. Do you have any standards or other documentation on your agency’s linear (or location) referencing strategy and systems? Request copies of any available documentation.
4. Detailed Description of Each LRS  
*Repeat this section as needed for each LRS in use by the Agency*

4.1. General overview

4.1.1. How is this LRS referred to (its “name”)?

4.1.2. What type of LRS is this (route/milepoint, link/node, control section, etc.)?

4.1.3. Briefly describe how the LRS is managed (e.g., computer application, hardware/software, etc.).

4.1.4. What documentation describes this LRS (obtain copies)?

4.1.5. What documentation exists for end-users, on how to determine and record locations, standard database fields, etc.?

4.1.6. How long has this LRS been in use?

4.1.7. Has it undergone any major revisions? If so, explain.

4.1.8. Whose responsibility is it to maintain and update the LRS, and to assure correct use of the LRS?

4.1.9. Do you have any plans or contingencies for converting to metric?

4.2. Use of this LRS

4.2.1. Who in this agency uses this LRS (e.g., what management systems), and what information is referenced to this LRS:

| General roadway characteristics system | Right-of-way |
| Traffic management (counts, volumes, etc.) | Videolog |
| Congestion management | Permit routing |
| Accidents | Maintenance |
| Bridges | Local road inventory |
| Pavement management | Rail (crossings, etc.) |
| Highway / work program development | Air / aviation |
| Project monitoring system | Public transportation |
| Engineering / design | Other: |
| Construction management | ____________________________ |
| HPMS | ____________________________ |
| Sign inventory | ____________________________ |

4.2.2. What end-user applications (GIS or other) make use of this LRS (work program development, etc.)?

4.2.3. To what degree is this LRS used and/or maintained and updated by DOT district offices?

4.3. Route definition, coding, resolution

4.3.1. How are routes defined? What roadway sections make up a route, and how are start and end points determined?
4.3.2. To which roadways does this LRS apply (state system, county, other public roads, etc.)?
   Note: specific cases like ramps and service roads are dealt with below.

4.3.3. How are the route IDs coded? Note: be specific concerning the meaning of individual characters and codes, the use of leading zeros, justification within the field, etc. Any documentation?

4.3.4. How many individual routes are there (approx.)?

4.4. Linear Referencing System control
   LRS control files (or tables, or diagrams) define the key components which control the LRS, and the relationships between them. LRS control elements may include routes, links, control points, mileage equations or other components. Data tables (or event tables) are not part of the LRS control.

4.4.1. What documentation describes the LRS control files (or tables, diagrams, etc.)?

4.4.2. Describe the control files used to manage the LRS (or reference the documentation).

4.4.3. Are mileage equations used? If so, describe their use and function.

4.4.4. Describe any other tables that comprise the LRS database, and the database structure.

4.4.5. What are the strengths and weaknesses of the LRS control database?

4.5. Field practices / data collection

4.5.1. Are mileposts or reference posts (i.e., signs) used in the field? Yes No
   If so:
   a) When were they established?
   b) Have they been maintained, and are there any maintenance issues?
   c) Are they considered to be accurate?
   d) Is there any estimate of maintenance costs?

4.5.2. How are ‘correct’ route lengths determined in the field (e.g., use of DMIs)?

4.5.3. What “centerline” is used to determine road length (e.g., right lane)?

4.5.4. Where exactly are the start and end points of routes (e.g., within an intersection)?

4.5.5. How are the measures (the “locations”) of point and linear events determined:
   a) in the field (e.g., mileposts or reference posts)?
   b) in the office (e.g., Straight Line Diagrams, ‘route log’ or ‘log mile’ listings, or computer applications)? Note: if possible, get a sample SLD

4.5.6. If Straight Line Diagrams are used:
   a) do they have route IDs on them (e.g., as used in the LRS control database)?
   b) do they have milepoints on them?

4.5.7. What problems or issues are there in the field (or office) for those using the LRS for their data collection?
4.5.8. What are your standards (or practices) for linear measurement accuracy (e.g., accuracy tolerance in urban/rural areas, accuracy for different feature types, etc.)?

4.5.9. If a route is re-measured and found to differ from the old length, is there a tolerance below which the official length is left unchanged?

4.5.10. Other?

4.6. GIS implementation (if implemented)

4.6.1. What GIS software is currently used?

4.6.2. What process was used to “implement” this LRS using GIS?

4.6.3. Have all roads handled by the LRS been implemented in GIS?

4.6.4. Describe the GIS base map (centerline file) used:
   a) Original source of centerlines:
   b) Scale:
   c) Development process:
   d) Accuracy/quality:
   e) Other:

4.6.5. Quality control of the GIS base map:
   a) What quality control has been done on the LRS implementation in the GIS base map?
   b) Have mismatches been identified between field-measured lengths and GIS lengths?
   c) Are there discrepancies between the LRS and the coding in the GIS base map (e.g., differences in section lengths, problems with interchange alignments, etc.)?

4.6.6. GIS base map update procedures:
   a) What update procedures are used for the GIS base map?
   b) Is the GIS base map kept synchronized with the LRS (e.g., if the linear measures for a route are updated in a relational database)? If so, what procedures are used?

4.6.7. If local roads (some or all) are included, describe:
   a) Source of the local roads centerlines:
   b) How local road centerlines were integrated:
   c) How local roads (and their routes) are updated and maintained:
   d) Other:

4.6.8. To what degree have the measures in the GIS been calibrated?

4.6.9. How accurate (or inaccurate) are the locations of features as displayed in the GIS? Is this a problem?

4.6.10. How is linear referencing currently being used in the GIS:
Data display/mapping
Database query (e.g., select a location or road section on the map and get a report)
Determination of linear measures (e.g., to specify crash locations)
Automated data input (e.g., including graphic specification of locations)
Other custom applications (construction project information, work program, etc.)
Quality control of data
Integration and analysis of different event tables (e.g., identify accidents associated with specific pavement conditions)
To convert between different LRSs (*Note: LRS conversion does not require GIS, but a GIS application is often used)
Other:

4.6.11. What (other) issues or problems have there been with the GIS implementation?
4.6.12. What have been the (other) major benefits and successes of the GIS implementation?

4.7. Special roadway cases
How does your LRS (and GIS base map) handle each of the following special cases:

4.7.1. Divided highways
   a) How are attribute locations specified along the separate travel ways (e.g., an accident which occurs in the north-bound lane)?
   b) If divided highways are not specially handled, are there problems due to the separate travel ways having somewhat different lengths/measures?
   c) If divided highways are specially handled in the LRS, what constitutes a ‘divided highway’? (E.g., only highways with full access control? Highways with a certain type of median?)
   d) Are routes defined for separate travel ways? If so, how are the measures determined, and are they correlated between the different travel directions?

4.7.2. Ramps
   a) Are ramps included in the LRS?
   b) Where do the measures for a ramp begin (e.g., at the gore point)?
   c) Are acceleration/deceleration lanes considered to be part of a ramp?

4.7.3. Approaches (at intersections, including ramp intersections).
   ◆ Especially, how is a ‘Y’ intersection handled? Is a separate route defined for one of the legs?

4.7.4. Alternate or overlapping routes
   a) For the case illustrated at right, does the LRS use coincident routes (measures increase for both routes along the common section), or is there a gap for the alternate route?
   b) Are multiple road/route name aliases supported for alternate routes?
   c) If a ‘primary’ route is designated, how is it selected?
d) Are attributes (events) along the common section associated with only the primary route, or can they be associated with either route?

e) Suppose there is a gap for the alternate route. For example, suppose the measures for route 5 stop at 2.5 miles at point A, then continue from 2.5 miles at point B. In this case, the location 'milepoint 2.5 on route 5' would be ambiguous, existing at 2 places (points A and B). Is this the case for this LRS? Yes ___ No ___ If so:

1) Has this posed any problems for you (e.g., is it possible for an accident at point A to be ambiguously located at '2.5 miles along route 5')?

2) If there are such gaps, do these potentially cause problems for analysis, such as for identifying high accident locations? For example, could a high accident location along route 5 span both legs, thus including two separate intersections?

4.7.5. If your routes are defined by county (or other jurisdiction), what happens when a route exits and reenters a county? Are there ambiguous measures (as there can be for a route with a spatial gap)?

4.7.6. One-way pairs (i.e., where a road divides into 2 one-way sections of different length)

a) If a separate route is defined for one leg of a one-way pair, what criteria determine if the leg is to become a separate route?

b) Are there any route ID coding conventions?

4.7.7. If local roads are included, are there any special accuracy or maintenance considerations?

4.7.8. Layered or tiered roads (e.g., a 2-level bridge).

4.7.9. Service roads (which parallel a limited access highway).

4.7.10. Individual lanes (including HOV lanes).

4.7.11. Associated facilities (truck runoff ramps, rest areas, emergency U-turns, etc.).

4.7.12. Rotaries: how is the situation illustrated at right addressed, where a portion of a rotary doesn’t belong to any of the intersecting routes?

4.7.13. Cul-de-sacs: is a standard direction (clockwise or counterclockwise) used for determining the direction of increasing measures?

4.7.14. Proposed highways: if measures are assigned, how are these integrated with the base map?

4.7.15. Locations of offset features (i.e., perpendicular offset from a route).

4.8. Attribute storage schemes

4.8.1. Is there a major, centralized ‘roadway characteristics’ database? If so, what is it called?

4.8.2. Are event tables ‘linearly normalized’, ‘linearly denormalized’, or a hybrid?

4.8.3. Are any QA/QC procedures used to:
a) verify that a linear event table covers the entire network? For example, every section of roadway falls under a single jurisdiction; is there a routine to assure the ‘jurisdiction’ event table covers all roadways in the system?

b) verify that all event route IDs and milepoints are valid?

c) verify point events are not coded at ambiguous milepoints (i.e., at discontinuous routes that have continuous measures?)

d) other?

4.8.4. Are there any barriers to database query or analysis associated with the database structure?

4.9. Updates to the LRS and management of historical data

4.9.1. Briefly, what process is used to update the LRS (not the GIS data), due to reconstruction, new construction, abandonments, re-measurements, etc.?

4.9.2. Is there a system for tracking updates to the LRS over time? How are updates recorded?

4.9.3. Is there a system for notifying end users of updates to the LRS, so their event tables can be updated?

4.9.4. Are routes and/or events time stamped? ___ Yes ___ No If so, describe what the time stamps refer to (data entry data, effective/expiration dates, etc.), and how they are used.

4.9.5. Are historical alignments (and/or routes) stored:

a) in the LRS?

b) In the GIS data?

4.9.6. Are there procedures for comparing the records of an event table to assure that events are ‘synchronized’ with the current LRS (i.e., to identify any records that reference routes or portions of routes which have been updated)?

4.9.7. Are there procedures for keeping updates to the GIS network synchronized with updates to the LRS?

4.9.8. Consider a specific example, a realignment with reduction in route length. Suppose that a reconstruction project between milepoints 1.0 and 3.0 of a 10.0-mile route eliminates 0.1 miles from the route.

a) How are the route IDs modified?

b) How are the measures (and/or routes) updated along the full length of the original route (e.g., does the original section from 0.2 to 10.0 miles now measure from 0.1 to 9.9 miles)?

c) Are field markers updated (with new measures)?
d) For on-line event tables (in the centralized “roadway characteristics” database), are the measures for events referenced to the updated route updated accordingly? If so, is the process automated or manual?

e) How are updates handled for event tables other than in the centralized database (i.e., used by different divisions)?

4.9.9. Procedures used for other types of updates. Using the questions posed above under 4.9.8 as a model, how are each of the following cases updated in the LRS, with regards to the route IDs, measures, field markers, storage of historical data, etc.

a) Roadway realignment with increase in length (any difference from the update process for a reduction in length, as in 4.9.8?):

b) Change to the route identifier (e.g., if highway jurisdiction changes from state to county):

c) Correction to route measures without any change to the roadway alignment (e.g., due to re-measurement in the field):

d) Addition of a new roadway (and route):

e) Addition of a new portion to an existing route, and the end or beginning of the route:

f) Deletion of an entire roadway/route:

g) Deletion of a portion of a route, from the beginning, middle or end of the route:

h) Creation of a new node (e.g., due to addition of a new road), in the middle of a route, with a newly-determined measure:

4.9.10. What needs do you see for managing historical data, which are not currently being met?

5. HPMS Submission

5.1. Have you developed a separate or modified LRS to meet HPMS submission requirements? If so, please elaborate.

6. Data Integration

6.1. Data transfer between information systems

6.1.1. Consider a roadway characteristic such as Average Annual Daily Traffic (AADT), which is typically used by many information systems. When new AADTs are determined, how are the new values transferred to other information systems (e.g., traffic modeling, bridges, railroad crossings, etc.)?
6.2. Integration of different LRSs

6.2.1. To what degree are your multiple LRSs integrated?
   a) Are you able to translate measures from one LRS to another? For which LRSs?
   b) Are you able to map features using different LRSs?
   c) Are you able to perform queries with custom applications, drawing from data sets using different LRSs?
   d) Are you able to perform ad hoc queries, from data sets using different LRSs?

6.2.2. What major problems and/or successes have you had integrating data located by different LRSs?

6.3. Integration with GPS and other geographically referenced data

6.3.1. Are you integrating GPS data with linearly referenced data? If so, please elaborate.

6.3.2. Does your GIS base map have link attributes? If so, what are the attributes, and how are these integrated with linearly referenced data?

6.3.3. Are you integrating linearly referenced data with any point or polygon data (e.g., for any specific projects)?

7. Use of Related Technologies

7.1. Describe any GPS activities related to linear referencing, such as:
   7.1.1. Refinement of the LRS measures?
   7.1.2. Refinement of the GIS base map?
   7.1.3. Resolution of discrepancies between the LRS and GIS base map?
   7.1.4. Data collection?

7.2. Describe any use of video logging, and the use of linear or other referencing systems for locating video footage.

7.3. Describe any use of other technologies related to linear referencing:
   7.3.1. Data warehousing:
   7.3.2. Intelligent transportation systems (ITS):
   7.3.3. Other:

8. Relationship to Other Modes of Transportation

8.1. Are you considering the use of linear referencing to support other modes of transportation, such as for supporting analysis and modeling of transit information?
This questionnaire includes information compiled from various system documents and numerous interviews. In some cases, the terminology has been changed from the source documents and interviews, for consistency with the overall handbook.

Brief Overview

The Missouri Department of Transportation is in the process of developing the MoDOT Transportation Management System (TMS), an automated system that includes a collection of applications to integrating multiple management systems (in Phase 1: bridge, pavement, safety, congestion, traffic monitoring and inter-modal inventory). TMS will serve as the MoDOT enterprise transportation database, with these goals:

- incorporate legacy databases through custom loading routines
- provide data access and maintenance tools to other offices
- enable query and reporting through a common interface (Impromptu and ArcView)
- move toward migration of systems to be directly incorporated in the enterprise database.

At the heart of the TMS is the Travelways system, providing a standard location reference system and methods for locating the events and features of interest to MoDOT.

The Travelways system supports a number of location referencing methods, including:

- log units (milepoints or kilometer points, based on an enterprise linear referencing system)
- distance from a known point along a route
- GPS coordinates (not currently used, but supported for future use)
- address geocoding (based on TIGER addresses).

Several special features of the Travelways system include:
extensible to all modes of travel along linear features (roadways, railways, waterways, airways, etc.)

* separate routes defined for both directions of travel on all bi-directional Travelways

* complete management of historical data
  * transaction-based management within a relational database (Oracle), fully integrated with a GIS base map
  * common access to the centrally maintained enterprise system by all MoDOT offices

* integrated management of core roadway attributes (e.g., functional class, national highway system, etc.).

To aid in the transition to the Travelways system, a previously used LRS (the ‘old system’) is currently supported within the TMS application. This ‘old system’ is only supported to aid in the one-time conversion of data from legacy systems to TMS and to aid in interfacing from legacy systems to TMS until the legacy systems are replaced. It is considered a strong point to develop and support a single, enterprise-wide LRS, rather than accommodating multiple LRSs and translations between them.

Although the TMS is currently in development, key functionality has been demonstrated through a prototype. The system is the result of two years of analysis work followed by approximately 15 months of concentrated development (to date).

9. **Persons Interviewed**

Personnel were interviewed on July 14-15, 1997, along with some phone interviews held prior to and following these dates. Interviewed personnel included:

Lee Ann Kell, Computer Programming Engineer, Information Systems
Karen Lister, Programmer Analyst, Information Systems
Charles Coldwell, Consultant (to Information Systems)
Greg Hayes, Bridge Maintenance Systems
Lee Standard, Bridge Maintenance Systems
Allan Heckman, Traffic Monitoring System
Eileen Rackers, Safety Management System
Lynn Stacy, Travelways Group
Steve Vance, Consultant (to the GIS Section)

10. **Organizational Information**

10.1. **What office is responsible for development and maintenance of the agency’s linear referencing systems? Describe its responsibilities.** The Office of Transportation Management Systems (OTMS) is responsible for all transportation management information systems. Within OTMS, the Travelways Section will be responsible for maintaining the Travelways system.

10.2. **What office is responsible for coordinating GIS activities? Describe its responsibilities.** The GIS Section is located within in the OTMS.
11. Overview of Current Use of Linear Referencing

11.1. Can you name and briefly describe each of the linear referencing systems currently in use in your agency? The Travelways system is a new, enterprise LRS designed for use all transportation modes, and by all management systems. The new LRS will be used in TMS when the system is rolled out. The “old system,” a county-based route system maintained on a mainframe computer (since 1967), will only continue to be used while legacy systems are being maintained. The Travelways system is a much more robust LRS, including many new features not present in the “old system.”

11.2. What are the major issues you face, as a department, with regard to linear referencing? The “old system” had a number of limitations which, given newly available technology, warranted development of a completely new enterprise LRS. For example, the mainframe system maintained three concurrent log systems (‘basic’, ‘geometric’ and ‘current’), and some offices and Districts effectively maintained their own LRSs (generally with differences in milepoints, not routes). Updates were not synchronized between different offices, so that they each maintained different log miles. There was no consistent management of historical data. Interchanges were not fully represented (routes met at a single ‘point’, regardless of divided highways), so that all accidents or signs at an interchange would be coded to the same point. Where routes left and re-entered a county, the milepoints would restart where they left off, creating two points on a route with the same milepoint (the same was true for alternate routes on overlapping route sections). Milepoints were reset to zero where a highway changed between divided and undivided. With the old system, data analysis could be “80% determining and rectifying location, and 20% analysis.”

The new system rectifies these limitations and provides for systematic integration of all management systems. As well, centralized management of updates to the system will simplify record keeping by individual offices.

11.3. What formal process, if any, was used for development of your linear referencing system(s), e.g., Information Engineering? The Travelways system was developed using Composer CASE tool (Sterling Software, previously owned by Texas Instruments). Composer was used to develop the logical data model, as well as applications that enforce the data model integrity and embedded business rules.

11.4. Describe any current initiatives you have for revising / expanding your linear (and location) referencing. The TMS and Travelways system are the current initiatives.

11.5. Do you have any standards or other documentation on your agency’s linear (or location) referencing strategy and systems? See section 4.1.4.

12. Detailed Description of Each LRS

12.1. General overview

12.1.1. How is this LRS referred to (its “name”)? The Travelways system.

12.1.2. What type of LRS is this (route/milepoint, link/node, control section, etc.). The Travelways system relies on a route/milepoint LRS, using continuous routes where the ‘log units’ (milepoints and kilometer points) increment continuously throughout the length of each route. Both milepoints and ‘kilometer points’ are
supported, thus the term ‘log units’ is used by MoDOT rather than ‘milepoint’. The system also supports reference points, or ‘distance from a known point’, mainly for data input (distances can be in English or metric units). In Phase I, the only ‘known points’ supported are intersections. In the future the system will also support GPS coordinates and street addresses.

In the GIS coverage, two different route systems have been created (but only the first route system is represented in the enterprise database):

- one to support the new business rules for the ‘new’ LRS, and
- one to support the old business rules for the ‘old system’.

The route system for the ‘old system’ is strictly used as a “cross-reference” (or “crosswalk” as referred to by MoDOT) for one-time conversions and on-going interfaces need with legacy systems. TMS users will not use this ‘old system’ for any of the data entry or querying.

In the database, where events are associated to locations (or ‘log units’), a corresponding county-based log (beginning log of 0 at each county line) is calculated and stored with each continuous log (each log, continuous or county, supports only new business rules). Storing this value facilitates allowing users to more easily use log units within a county (county-based logs) when doing ad hoc querying. The ‘old system’ did not support the concept of continuous logs, thus data entry and querying allows the users to enter in continuous logs or county-based logs (along with specifying a county).

12.1.3. Briefly describe how the LRS is managed (e.g., computer application, hardware/software, etc.). LRS control tables reside within the integrated Transportation Management System (TMS), an enterprise Oracle database. The Travelways system will be maintained through the Travelways Maintenance Application, a GIS application (ArcStorm or Arc/Info) which will automatically synchronize updates between the GIS data and the TMS relational database.

12.1.4. What documentation describes this LRS (obtain copies)? The Transportation Management System documentation is under development. Current draft documents include the “Travelway Management System Summary Design” and the “Travelways System Detail Design”. Another draft document summarizes business rules for location referencing and for specific types of roadways and Travelways.

12.1.5. What documentation exists for end-users, on how to determine and record locations, standard database fields, etc.? End-user documentation is currently being developed and will be released with the rollout of TMS. It includes such things as changes to business rules, any ‘assumptions’ of ‘need to know’ about the system and data, data dictionary, etc.

12.1.6. How long has this LRS been in use? The LRS development is nearing completion.

12.1.7. Has it undergone any major revisions? If so, explain. N/A.
12.1.8. Whose responsibility is it to maintain and update the LRS, and to assure correct use of the LRS? The Travelways section of the Office of Transportation Management Systems (which also includes the GIS Section).

12.1.9. Do you have any plans or contingencies for converting to metric? The Travelways system includes both English and metric units of measure, and either can be used for data input and query purposes.

12.2. Use of this LRS

12.2.1. Who in this agency uses this LRS (e.g., what management systems), and what information is referenced to this LRS: The TMS currently interfaces to the systems checked below. Interfaces to other systems will be added over time.

<table>
<thead>
<tr>
<th>X</th>
<th>General roadway characteristics system</th>
</tr>
</thead>
<tbody>
<tr>
<td>X</td>
<td>Traffic management (counts, volumes, etc.)</td>
</tr>
<tr>
<td>X</td>
<td>Congestion management</td>
</tr>
<tr>
<td>X</td>
<td>Accidents</td>
</tr>
<tr>
<td>X</td>
<td>Bridges</td>
</tr>
<tr>
<td>X</td>
<td>Pavement management</td>
</tr>
<tr>
<td>___</td>
<td>Highway / work program development</td>
</tr>
<tr>
<td>___</td>
<td>Project monitoring system</td>
</tr>
<tr>
<td>___</td>
<td>Engineering / design</td>
</tr>
<tr>
<td>___</td>
<td>Construction management</td>
</tr>
<tr>
<td>___</td>
<td>HPMS</td>
</tr>
<tr>
<td>___</td>
<td>Sign inventory</td>
</tr>
</tbody>
</table>

12.2.2. What end-user applications (GIS or other) make use of this LRS (work program development, etc.)? The goal is to migrate various management system into the TMS over time, and to have all end-user applications work directly with the fully integrated TMS.

Several applications have been developed to demonstrate TMS functionality. A generic ‘Travelway Selection Criteria’ screen enables users to select roadways of interest using any of the supported referencing methods. A Highway Capacity software interface computes highway capacity based on user-selected criteria (i.e., enabling what-if analysis).

12.2.3. To what degree is this LRS used and/or maintained and updated by DOT district offices? The LRS will not be maintained or updated in the Districts. A group (the Travelways section) of the Office of Transportation Management Systems (OTMS) will be responsible for maintaining and updating the ‘Travelways’, which includes conveying to the Districts and Divisions what Travelways changes/updates have been made. This ‘notification’ process has not yet been defined. A notification process will also be defined for Districts and Divisions to use to communicate needed changes to travelways to OTMS.

12.3. Route definition, coding, resolution

12.3.1. How are routes defined? What roadway sections make up a route, and how are start and end points determined? Each numbered (or lettered or named) route is represented in the LRS by one travelway for each direction of travel. A
Travelway is defined as a “conceptual or publicly used path/corridor for movement of vehicles, goods, and/or people.” Travelways may include roadways, railways, waterways, airways, etc.

In Phase I, Travelways are defined along roadways only (other modes will be supported in future phases). Routes are therefore defined corresponding to numbered or named roadways (e.g., US 54 East, US 54 West, MO 94 North, etc.).

A logical Travelway identifier consists of three components:
- Travelway designation (US, MO, etc.),
- Travelway name (usually the posted number or name), and

Additional identifiers may include the state name, district number, county name or city name, as needed, to assure uniqueness. A unique internal identifier is used for each travelway to assure integrity of the physical database. The unique internal identifier corresponds to the appropriate ‘route’ identifier created in the GIS.

For local roads (county roads and city streets), the Travelway name is the full road name. The on-line application in TMS will allow users to choose travelways by selecting these items from lists. For data conversions and interfaces, the legacy systems must include the correct designation and names; direction can be determined/assumed as primary if the other two items are given.

Standard roadway designations used to identify Travelways (in route designation hierarchy) include:

<table>
<thead>
<tr>
<th>Designation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>IS</td>
<td>Interstate</td>
</tr>
<tr>
<td>US</td>
<td>U.S.</td>
</tr>
<tr>
<td>M</td>
<td>Missouri numbered</td>
</tr>
<tr>
<td>O</td>
<td></td>
</tr>
<tr>
<td>AL</td>
<td>Alternate marked route</td>
</tr>
<tr>
<td>RT</td>
<td>Missouri lettered route</td>
</tr>
<tr>
<td>LP</td>
<td>Loop</td>
</tr>
<tr>
<td>BU</td>
<td>Business marked route</td>
</tr>
<tr>
<td>SP</td>
<td>Spur</td>
</tr>
<tr>
<td>OR</td>
<td>Outer road (see section 4.7.9)</td>
</tr>
<tr>
<td>RP</td>
<td>Ramp</td>
</tr>
<tr>
<td>CO</td>
<td>Connector (for a wye leg)</td>
</tr>
<tr>
<td>CST</td>
<td>City street</td>
</tr>
<tr>
<td>CR</td>
<td>County road (includes all ‘local’ roads)</td>
</tr>
<tr>
<td>PV</td>
<td>Private drives</td>
</tr>
<tr>
<td>T</td>
<td></td>
</tr>
</tbody>
</table>

Generally, even numbered Travelways are west-east, and odd numbered Travelways are north-south. For Travelways without an explicit direction, the coordinates for the beginning and ending of the Travelway are used to determine if the Travelway is more west-east or north-south.

Outer roads (designated OR) require an additional direction, indicating the direction the outer road is offset from the mainline to which it is an outer roadway. For example, a single mainline Travelway may have two outer roads (e.g., offset north and south).
Travelway routes are defined for both directions of travel for all roadways (one-way roads have a single Travelway). The milepoints for each direction increment in the direction of traffic flow. The lengths between intersections may differ for opposing directions, although these are generally the same for undivided highways. The south- and eastbound directions are designated as ‘primary’. Direction-specific events are referenced to the appropriate Travelway. For example, accidents (which are being integrated with TMS) will be located in the future on the travelway for the direction of travel on which the accident occurred. During conversion of legacy accidents data, accidents will be located on the travelway of primary direction if no direction is indicated in the legacy system (a rule followed by all data conversions and interfaces).

The migration from the ‘old system’ to dual-direction Travelways will require training, and some ‘culture shock’ is expected. In the field, use of the ‘log books’ may, in some cases, be more complicated (although users will now be able to specify location as a distance from a known feature). The design of the ‘log book’ for the new LRS has not yet been determined. Increased complexity will depend greatly on exactly what the business needs are; different areas of the business may need more complexity than others. For instance, if logging of accidents on undivided travelways needs only to be done to the primary direction, then only the logs for the primary direction of undivided travelways need to be included in the log book for that business area.

Ad hoc queries and analysis will be more difficult with dual-direction Travelways, thus there are plans to develop tools to simplify certain types of queries. Users look forward to more easily accessing roadway features and characteristics in spatial order, for either travel direction. Dual-direction Travelways are generally anticipated as a major improvement by end users.

Ramps are named based on the roadways they connect (e.g., ‘Ramp 54W to 63N’). Ramp direction is derived from the direction of the route traveled to (if the ramp ends at a ‘T’ intersection, the direction of travel is used). Some roadways that appear to be ‘ramps’ in complex interchanges may actually carry the ‘mainline’ route (travelway) through the interchange. For example, in the figure below, US 63 N overlaps US 54 W and ‘splits off’ at the ‘ramp’. Therefore, the travelway ‘RP US 4 W TO US 63 N N’ is built along this arc (or link), but the arc also carries the route for mainline US 63 N (the primary travelway).
12.3.2. To which roadways does this LRS apply (state system, county, other public roads, etc.)? All public roads (state, county and city) are included in the Travelways system. Some private drives are included (named ‘Private Drive’). In addition, there are plans to incorporate roadways for a ring of counties surrounding Missouri in the future.

12.3.3. How are the route IDs coded? An internal numeric ID is used within TMS. Components of the Travelway logical identifier are described in section 4.3.1.

12.3.4. How many individual routes are there (approx.)? One for each direction of travel for each numbered, lettered or named roadway. Main Street in Columbia and Main Street in Jefferson City would be four separate travelways (one for each direction in each city).

12.4. Linear Referencing System control

LRS control files (or tables, or diagrams) define the key components which control the LRS, and the relationships between them. LRS control elements may include routes, links, control points, mileage equations or other components. Data tables (or event tables) are not part of the LRS control.

12.4.1. What documentation describes the LRS control files? See section 4.1.4.

12.4.2. Describe the control files used to manage the LRS (or reference the documentation). A detailed logical data model was developed to manage the Travelways system. The core of the Oracle database includes the following entities.

- A Travelway (defined in 4.3.1) is logically identified by a Travelway designation, a unique name, and a direction designation. This has a logical one-to-one correspondence with the Arc/Info Route Attribute Table (RAT).

- A Travelway Segment is the portion of a Travelway defined as beginning and ending at Travelway intersections or a county line. This has a logical one-to-one correspondence with the Arc/Info Section Table (SEC).
• The Travelway Location table stores all specific point locations for all Travelways (e.g., segment begin/end points, intersections, accidents, bridge ends, etc.). The continuous log unit data logically relates to the From Measure and To Measure fields in the Arc/Info section table.

• A Travelway Intersection is a point at which two or more Travelways cross each other, either ‘At Grade’ (physically come together) or ‘Not At Grade’ (pass over or under one another). This logically relates to the Arc/Info Node Attribute Table (NAT), using the same identifier. Intersections are not currently named, but names can be assigned to intersections (if done, this will be an on-going, evolving process by the business).

• The Intersection Location table joins the Intersection table to the Location table, storing where each intersection occurs along each route.

• A Travelway Interchange includes multiple Travelway intersections that are within the boundary of a defined interchange.

• An Overlapping Travelway occurs when two or more Travelways occupy the same physical pavement structure. This excludes the case where two different directions reside on undivided pavement. For example, Route A East and Route A West reside on the same physical, undivided pavement structure, but they are not overlapping.

The basics of the Travelways system can be summarized around Travelway Segments, Travelway Intersections and Travelway Locations. Travelways are composed of contiguous segments connected by intersections. All intersections have a location on all intersecting Travelways.

In the figure below, for example, US 54 East intersects MO 94 East at intersection #5521 at log 86.987 (location D), which may have a Travelway Location ID of 1193303; but MO 94 East intersects US 54 East at log 15.558 (D), which may have a Travelway ID of 993002. Each travelway involved in a given intersection reaches that intersection at its own log. A user can look at the intersection from one travelway’s perspective and determine what other travelways also come into that same intersection.
Travelway Segments, Intersections, and Locations

All location specifications are stored in the Travelway Location table. Each record stores one location along one route, with both the continuous and county log units, and with both milepoints and kilometer points for each of these (to simplify queries and speed response). Individual event tables do not explicitly store locations (as in the Travelway ID, begin milepoint, end milepoint). Instead, they store a pointer (a foreign key) to the location details stored in the Travelway Location table. This is conceptually represented in the figure below. This relational structure allows a log unit value to be changed by updating only the Travelway Location table for that particular log unit, so that by virtue of the foreign key the accident record is always ‘connected’ to the most current log unit, even when realignments occur.

<table>
<thead>
<tr>
<th>Accident Table</th>
<th>Travelway Location Table</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acciden...</td>
<td>Location</td>
</tr>
<tr>
<td>t ID</td>
<td>Data</td>
</tr>
<tr>
<td>1896</td>
<td>...</td>
</tr>
<tr>
<td>3123</td>
<td>...</td>
</tr>
<tr>
<td>4009</td>
<td>...</td>
</tr>
<tr>
<td>3880</td>
<td>...</td>
</tr>
<tr>
<td>4585</td>
<td>...</td>
</tr>
</tbody>
</table>

Other entity types in the data model record information on where a Travelway enters and leaves a specific county or city, the points at which a Travelway begins or ends being divided or undivided, and others which classify or further define the Travelway in some way.
12.4.3. Are mileage equations used? If so, describe their use and function. Mileage equations are not used, except for engineering stationing (not supported in Phase I).

12.4.4. Describe any other tables that comprise the LRS database, and the database structure. See 4.4.2.

12.4.5. What are the strengths and weaknesses of the LRS control database? The Travelways system logical data model has been designed to meet enterprise business rules for location referencing, and the detailed requirements of the TMS. The system is expected to meet the needs of the Department’s information users.

12.5. Field practices / data collection

12.5.1. Are mileposts or reference posts (i.e., signs) used in the field? Yes No

If so:

a) When were they established? Some were established long ago (mid-1960s?), mainly on interstates and US routes.

b) Have they been maintained, and are there any maintenance issues? They have been maintained to a degree, but will not be used in the Travelways system at this time (in the future they may be used as reference points).

c) Are they considered to be accurate? Some mileposts are known to have inaccurate milepoints. In the future, it is desired to obtain an accurate log listing for the mileposts, and use them as reference posts.

d) Is there any estimate of maintenance costs? No.

12.5.2. How are ‘correct’ route lengths determined in the field (e.g., use of DMIs)? Travelways started with existing mileages from the ‘old system’, which were generally taken for engineering stationing records. Routes are not all re-measured on a regular basis. County roads have been inventoried every 2 years, and re-measured with a DMI (or perhaps an odometer in some cases). The lengths of local roads added to the Travelways system have generally been determined by the GIS centerline lengths.

For new construction, measures are obtained from the design plans. In the future, these will come directly from electronic plans.

12.5.3. What “centerline” is used to determine roadway length (e.g., right lane)? Travelway lengths are determined by actual road or traveled miles in the direction of travel. There is no specific rule as to which lane corresponds to the hypothetical ‘centerline’.

12.5.4. Where exactly are the start and end points of routes (e.g., within an intersection)? For Travelways that start within an intersection, the starting point is at the hypothetical intersection of Travelway ‘centerlines’. For some cases, such as the dog leg intersection at right, business rules are yet to be established. When undivided Travelways intersect at a 4-way stop, say Route A East and West and Route B North and South, Route A East intersect Route B North and Route B South at ...
12.5.5. How are the measures (the “locations”) of point and linear events determined:

a) in the field (e.g., mileposts or reference posts)? Mileposts are available on some interstates and US routes (with some known problems with displayed mileages). More often, log books listing the milepoints of static features along all routes are used. (The only ‘static feature’ available for Phase I of TMS is intersections. Future releases hope to support using the logs of other static features stored in the database such as bridge ends, signs, etc.)

b) in the office? The ‘log books’ are used, which record the milepoints of features along all routes. Currently, log books are available for the ‘old system’. In the future, log books may be generated directly from the Travelways system, with both county and continuous routes, and with milepoints (and perhaps kilometer points) for Travelways in both travel directions. The complexity of the log books can be tailored to the specific application, as described in section 4.3.1.

12.5.6. If Straight Line Diagrams are used:

a) do they have route IDs on them (e.g., as used in the LRS control database)? N/A.

b) do they have milepoints on them? N/A.

12.5.7. What problems or issues are there in the field (or office) for those using the LRS for their data collection? The use of separate Travelways for both directions of travel created additional overhead, in that much data needed to be populated in both directions. To minimize this overhead, a routine was developed to automatically transfer data from one direction to the other. End users found this method to be very effective.

12.5.8. What are your standards (or practices) for linear measurement accuracy (e.g., accuracy tolerance in urban/rural areas, accuracy for different feature types, etc.)? Most data are currently recorded to 0.01 miles, while some (e.g., functional class) are recorded to 0.001 miles.

12.5.9. If a route is re-measured and found to differ from the old length, is there a tolerance below which the official length is left unchanged? Not at this time.

12.5.10. Other?

12.6. GIS implementation (if implemented)

12.6.1. What GIS software is currently used? Arc/Info and ArcStorm have been (and will be) used to develop and maintain the Travelways system.

12.6.2. What process was used to “implement” this LRS using GIS? The GIS roads layer is primarily derived from TIGER data, with the geometry of divided highways, interchanges and other special features added as needed. Some centerline data have been integrated from more accurate sources (e.g., St. Louis roads based on GPS data). Routes are being coded manually and with semi-automated tools. Beginning and ending measures (based on log books for the ‘old system’) are being entered for each arc.

12.6.3. Have all roads handled by the LRS been implemented in GIS? All roads in the LRS are currently being added to the GIS base map.

12.6.4. Describe the GIS base map (centerline file) used:
a) **Original source of centerlines:** US Bureau of the Census TIGER data.

b) **Scale:** Approx. 1:100,000.

c) **Development process:** Initial state system centerlines were based on refined TIGER data. Local roads are now being added from 1995 TIGER data through conflation.

d) **Accuracy/quality:** Spot checks are used during the development effort. All routes will eventually be checked for accuracy.

e) **Other:**

12.6.5. **Quality control of the GIS base map:**

a) **What quality control has been done on the LRS implementation in the GIS base map?** The GIS base map is under development. Quality control does or will include full QA of routes (e.g., start and end points), assure road names agree during conflation, spot checking, performing ‘frequencies’ to identify invalid codes, etc.

b) **Have mismatches been identified between field-measured lengths and GIS lengths?** Yes, but not systematically. GIS centerline lengths are compared with the county road inventory ‘log mile’ lengths, as part of ongoing QA/QC procedures.

c) **Are there discrepancies between the LRS and the coding in the GIS base map (e.g., differences in section lengths, problems with interchange alignments, etc.)?** Such discrepancies exist, but are currently being resolved in the base map.

12.6.6. **GIS base map update procedures:**

a) **What update procedures are used for the GIS base map?** The Travelways Maintenance Application (specifications completed, but to be developed) will perform updates in ArcStorm (or Arc/Info) and transfer the updates to the appropriate Oracle tables.

b) **Is the GIS base map kept synchronized with the LRS (e.g., if the linear measures for a route are updated in a relational database)? If so, what procedures are used?** Yes, the Travelways Maintenance Application will keep the Arc/Info and Oracle databases fully synchronized.

12.6.7. **If local roads (some or all) are included, describe:**

a) **Source of the local roads centerlines:** Primarily 1995 TIGER data, and some local data (e.g., St. Louis road centerlines).

b) **How local road centerlines were integrated:** Local roads are currently being integrated with the state base map by conflation of the 1995 TIGER data. As new nodes are added, their milepoints are being calibrated. Routes (Travelways) are being defined on local roads based on their road names.

c) **How local roads (and their routes) are updated and maintained:** This will be a challenge. One option will be to provide data to Districts, and have them check for changes.

d) **Other:**
12.6.8. To what degree have the measures in the GIS been calibrated? Beginning and ending measures are being coded for each arc on the state system (mainly from 'old system' log books). These are generally recorded to 0.01 miles. Prior to rolling out Phase I of TMS, key points (e.g., county boundaries, where overlaps start/stop, where divided facilities begin/end) are being updated to three decimal places. Milepoints for local roads are being determined from GIS centerline lengths.

12.6.9. How accurate (or inaccurate) are the locations of features as displayed in the GIS? Is this a problem? The accuracy has not been assessed, but depends on the source data for a particular feature. Currently, the older GIS data is being used to generate some maps. Due to the differences in LRS used in legacy systems throughout the Department and the correctness of the different data being converted, the accuracy of the placement of the data on travelways is a good as it can be at this time (given those unknowns). For current GIS mapping, the accuracy has not been considered a problem.

12.6.10. How is linear referencing currently being used in the GIS:

X  Data display/mapping

___ Database query (e.g., select a location or road section on the map and get a

___ Determination of linear measures (e.g., to specify crash locations)

___ Automated data input (e.g., including graphic specification of locations)

___ Other custom applications (construction project information, work program,

X  Quality control of data (especially, during development of the Travelways system)

___ Integration and analysis of different event tables (e.g., identify accidents

___ with specific pavement conditions)

X  To convert between different LRSs

X  Other: Development (i.e., coding) of the new system.

As the Transportation Management System comes on line, the GIS data is expected to be employed for more of the uses listed above.

12.6.11. What (other) issues or problems have there been with the GIS implementation? The efficient database structure for transactions often is not well suited for efficient or easy query access, whether the query tool is GIS or some other reporting tool. This is the case in TMS. An analysis version of the transactional database will be built and 'refreshed' periodically to ease query complexity.

12.6.12. What have been the (other) major benefits and successes of the GIS implementation? By fully integrating the GIS data with the Oracle database, the update process for the Travelways system will be simplified while assuring greater data integrity. The GIS implementation has also enabled data visualization of both legacy data and newly integrated data that was not previously possible on the enterprise scale. Current plans are for 100 GIS workstations to be rolled out to central and District offices for use with the system.
12.7. Special roadway cases

How does your LRS (and GIS base map) handle each of the following special cases:

12.7.1. Divided highways

a) How are attribute locations specified along the separate travel ways (e.g., an accident which occurs in the north-bound lane)? Each travel direction has its own Travelway, with measures incrementing in the direction of travel.

b) If divided highways are not specially handled, are there problems due to the separate travel ways having somewhat different lengths/measures? N/A.

c) If divided highways are specially handled in the LRS, what constitutes a 'divided highway'? (E.g., only highways with full access control? Highways with a certain type of median?) 'Divided' highways have opposing lanes of traffic physically divided by a 4 foot or greater flush median or some form of barrier defined by the AASHTO manual.

d) Are routes defined for separate travel ways? If so, how are the measures determined, and are they correlated between the different travel directions? Each travel direction has its own measures, increasing in the direction of traffic flow, using lengths measured in the field for each direction. For a given set of beginning and ending milepoint, an application provides the corresponding milepoints for travel in the opposite direction (relying on the Intersection Location table). For divided highways, the corresponding milepoints in the opposite direction may have a somewhat different length, but this is not a problem for general application needs.

12.7.2. Ramps

a) Are ramps included in the LRS? Yes. See sections 4.3 and 4.7.4c for more detail on ramps. Ramps always connect two Travelways.

b) Where do the measures for a ramp begin (e.g., at the gore point)? For a divided highway, at the physical, permanent gore, if possible, or the painted gore if there was no discernible physical gore. For an undivided highway, at the edge of pavement between the ramp and intersecting Travelway pavement or painted gore point.

c) Are acceleration/deceleration lanes considered to be part of a ramp? No, travelways for ramps do not include the acceleration/deceleration lanes. The lanes are simply another piece of data stored about a travelway.

12.7.3. Approaches (at intersections, including ramp intersections). At a ‘Y’ intersection, one leg is designated as the mainline. Where it corresponds to true traffic patterns, the primary travel directions (south and east) are connected for the two routes. There is no specific rule for a length above which a separate route is established for an approach.
12.7.4. Alternate or overlapping routes

a) For the case illustrated above, does the LRS use coincident routes (measures increase for both routes along the common section), or is there a gap for the alternate route? Coincident, overlapping routes are used. Undivided roadways support two Travelways, one for each direction, sharing the same pavement structure, but these are not considered to be overlapping.

b) Are multiple road/route name aliases supported for alternate routes? Yes, through an application.

c) If a ‘primary’ route is designated, how is it selected? An overlap may have a single primary and one or more alternate Travelways. The primary is selected by Travelway designation (Interstate, US, Missouri numbered route, Missouri lettered route, etc.), then by lowest number (or letter) within each Travelway designation.

When only ramps are overlapping each other, there is no clear rule to determine which ramp is primary. During the initial building of Travelways in the Oracle database for Phase I, a determination will be made as to which is primary. If it needs to be changed, it will be changed through the Travelways Maintenance procedure, yet to be developed.

d) Are attributes (events) along the common section associated with only the primary route, or can they be associated with either route? All attributes are associated with the primary route. When data are loaded into TMS from another system, any event data specified along an alternate route is automatically re-referenced to the primary route in TMS. Only the primary direction miles along the primary route are counted as official miles.

e) Suppose there is a gap for the alternate route. For example, suppose the measures for route 5 stop at 2.5 miles at point A, then continue from 2.5 miles at point B. In this case, the location ‘milepoint 2.5 on route 5’ would be ambiguous, existing at 2 places (points A and B). Is this the case for this LRS? ___ Yes ___ No

1) Has this posed any problems for you (e.g., is it possible for an accident at point A to be ambiguously located at ‘2.5 miles along route 5’)? This was a problem in the ‘old system’, but the Travelways system uses continuous mileages along coincident sections.

2) If there are such gaps, do these potentially cause problems for analysis, such as for identifying high accident locations? For example, could a high accident location along route 5 span both legs, thus including two separate intersections? N/A.

12.7.5. If your routes are defined by county (or other jurisdiction), what happens when a route exits and reenters a county? Are there ambiguous measures (as
there can be for a route with a spatial gap)? This was a problem in the ‘old system’, but the Travelways system uses continuous mileages for routes which exit and reenter a county.

12.7.6. One-way pairs (i.e., where a road divides into 2 one-way sections of different length)

a) If a separate route is defined for one leg of a one-way pair, what criteria determine the leg to become a separate route? By default, each direction of travel has its own Travelway, thus legs always have separate routes.

b) Are there any route ID coding conventions? The Travelway logical identifier includes a direction suffix as one component (see section 4.3.1).

12.7.7. If local roads are included, are there any special accuracy or maintenance considerations? Not at this time. There is some interest by local agencies (cities, MPOs, etc.) to have access to TMS.

12.7.8. Layered or tiered roads (e.g., a 2-level bridge). Each direction would have a separate Travelway.

12.7.9. Service roads (which parallel a limited access highway). In MoDOT ‘frontage road’ is a general term for both ‘outer roads’ which fall within the highway right of way, and ‘service roads’ which fall outside the right of way. Each travel direction of outer roads and service roads will be added as its own Travelway.

12.7.10. Individual lanes (including HOV lanes). Travelways are not created for individual lanes, including HOV lanes. Lanes are an attribute for each travel direction, numbered for each travel direction starting from the inside lane. The lane type is coded as: driving lane, right turn lane, left turn lane, or continuous left turn lane.

12.7.11. Associated facilities (truck runoff ramps, rest areas, emergency U-turns, etc.). These will not be included in Phase I.

12.7.12. Rotaries: how is the situation illustrated at right addressed, where a portion of a rotary doesn’t belong to any of the intersecting routes? This situation has not yet occurred. The rotary circle could be a separate Travelway, with overlapping Travelways for each incoming roadway.

12.7.13. Cul-de-sacs: is a standard direction (clockwise or counterclockwise) used for determining the direction of increasing measures? As for other roads, Travelways are established for both directions of travel around a cul-de-sac. The southbound or eastbound direction of the cul-de-sac ‘stem’ is considered the primary travel direction, thus counterclockwise around the cul-de-sac is primary. For local roads, the inclusion of cul-de-sacs initially depends on the accuracy of the GIS base map, which in turn depends on the accuracy of the TIGER line work that was merged with the coverage by conflation.

12.7.14. Proposed highways: if measures are assigned, how are these integrated with the base map? It is undecided at this time if centerlines for proposed roads will be added to the roads layer, or to a separate coverage. A ‘band’ may be added to the coverage for planning corridors. The activation date for a proposed road depends on the roadway status (see section 4.9.4).
12.7.15. Locations of offset features (i.e., perpendicular offset from a route).
Some database elements have attributes for offsets, for future use. Each application has its own rules for what the perpendicular offset is referenced to (centerline, edge of pavement, etc.).

12.8. Attribute storage schemes

12.8.1. Is there a major, centralized “roadway characteristics” database? If so, what is it called? The Transportation Management System (TMS).

12.8.2. Are event tables ‘linearly normalized’, ‘linearly denormalized’, or a hybrid?
On-line event tables within TMS are organized by functional area. The LRS control tables are further described in section 4.4.

12.8.3. Are any QA/QC procedures used to:

a) verify that a linear event table covers the entire network? For example, every section of roadway falls under a single jurisdiction; is there a routine to assure the ‘jurisdiction’ event table covers all roadways in the system? QA routines are built into the on-line applications for data entry. The data loads do not (or will not) always check for these cases, depending on the routine used.

b) verify that all event route IDs and milepoints are valid? Yes, a common procedure is used for all data loads.

c) verify point events are not coded at ambiguous milepoints (i.e., at discontinuous routes that have continuous measures? Not applicable.

d) other? If data are submitted by county, a routine verifies that routes are in the correct county.

12.8.4. Are there any barriers to database query or analysis associated with the database structure? Queries which involve event overlays are difficult to pose, due to the complexity of intersecting the route measures for the different event tables. This will be an issue for queries posed directly from the GIS, which may require development of a separate ‘event overlay’ routine.

Some event data are stored for both Travelways along bi-directional highways. Applications must take this into account so as not to ‘double count’ event data (e.g., roadway mileage). For some applications, end users must be familiar with the business rules to avoid misuse of the data.

12.9. Updates to the LRS and management of historical data

12.9.1. Briefly, what process is used to update the LRS (not the GIS data), due to reconstruction, new construction, abandonments, re-measurements, etc.?
An update process has been defined and is currently in the detailed design phase. A ‘Travelway Maintenance Application’ will be developed to maintain the Travelways system’s Oracle tables directly from an ArcStorm (or Arc/Info) application. (The Arc/Info Librarian was used previously, but did not have adequate security mechanisms.) This application will assure that the Oracle and GIS data are fully synchronized at all times.

In brief, when any element of the LRS is update, the affected Travelway Sections and Locations are deactivated (by setting ‘deactivate’ date fields), and new Sections and Locations are created as needed (with ‘activation’ date fields set accordingly).
12.9.2. Is there a system for tracking updates to the LRS over time? How are updates recorded? Updates to the LRS are recorded in the Travelway Section and Location tables by setting the ‘activation’ and ‘deactivation’ dates, as needed.

12.9.3. Is there a system for notifying end users of updates to the LRS, so their event tables can be updated? A formal system for notifying users of Travelway changes will be developed, communicating the type and nature of changes made. This may include access to a browser of a Travelway Change table, enabling users to view the sequence of changes over time (by route, by District, etc.). External users might be notified of changes by e-mail, posting to a web page, or other means. Notification will be needed to make users aware of travelway changes, in case they are then required, due to business rules, to make changes to their data. However, for data stored within TMS, updates to locations (e.g., changing log units due to realignments) will be taken care of in the Travelways Maintenance procedure (yet to be developed).

12.9.4. Are routes and/or events time stamped? Yes

12.9.5. Are historical alignments (and/or routes) stored:
   a) in the LRS? Yes.
   b) In the GIS data? Yes (once the Travelways Maintenance Application is completed). It has not yet been determined how updates will be stored in the GIS (e.g., combined with current alignments in a single coverage, or in a separate coverage).

12.9.6. Are there procedures for comparing the records of an event table to assure that events are ‘synchronized’ with the current LRS (i.e., to identify any records that reference routes or portions of routes which have been updated)? Not at this time.

12.9.7. Are there procedures for keeping updates to the GIS network synchronized with updates to the LRS? Yes (to be established in the Travelways Maintenance Application).
Consider a specific example, a realignment with reduction in route length. Suppose that a reconstruction project between milestone 1.0 and 3.0 of a 10.0-mile route eliminates 0.1 miles from the route.

a) How are the route IDs modified? Route IDs are not modified.

b) How are the measures (and/or routes) updated along the full length of the original route (e.g., does the original section from 0.2 to 10.0 miles now measure from 0.1 to 9.9 miles)? All Travelway locations are updated 'downstream' from the realignment (through 10.0 miles). The deactivation date is set for all affected locations in the Travelway Location file, and new locations are established with new activation dates. Each newly created Travelway location is linked back to its respective deactivated location (by a foreign key), which maintains the correspondence between old and new measures.

All Travelway sections overlapping the realigned portion are deactivated, and new sections are created and activated as needed.

c) Are field markers updated (with new measures)? Perhaps, for mileposts on interstate and US highways, but not necessarily in all cases.

d) For on-line event tables (in the centralized “roadway characteristics” database), are the measures for events referenced to the updated route updated accordingly? If so, is the process automated or manual? Consider an event (e.g., an accident) which occurred along the updated portion of the route. The old record would be deactivated, and a new record created with the same activation data as the new Travelway sections and locations. Certain types of events which occurred on the realigned section would not be automatically transferred to the new alignment (business rules need to be established for these special cases).

Now consider a linear event which spanned the realigned portion of the route (e.g., a resurfacing record from 0 to 5 miles). The Travelway Maintenance Application will deactivate the original record and create 3 new records for resurfacing at different dates: 0 to 1.0 miles, 1.0 to 2.9 miles (newly surfaced), and 2.9 to 9.9 miles.

e) How are updates handled for event tables other than in the centralized database (i.e., used by different divisions)? A formal process will be developed for notifying separate data managers of updates to the LRS. The log books (with milepoint and kilometer point listings) will be updated accordingly.

Procedures used for other types of updates. Using the questions posed above under 4.9.8 as a model, how are each of the following cases updated in the LRS, with regards to the route IDs, measures, field markers, storage of historical data, etc.

a) Roadway realignment with increase in length (any difference from the update process for a reduction in length, as in 4.9.8?): No.
b) Change to the route identifier (e.g., if highway jurisdiction changes from state to county): A Travelway History table stores changes to route names over time.

c) Correction to route measures without any change to the roadway alignment (e.g., due to re-measurement in the field): Travelway locations are adjusted by proportional interpolation along the new section length.

d) Addition of a new roadway (and route): Creation of new Travelways, Travelway Sections and Travelway Locations as needed.

e) Addition of a new portion to an existing route, and the end or beginning of the route: Creation of new Travelways, Travelway Sections and Travelway Locations as needed. Portions of old Sections or Locations would be deactivated, as needed.

f) Deletion of an entire roadway/route: Deactivation of appropriate Travelway Sections and Locations.

g) Deletion of a portion of a route, from the beginning, middle or end of the route: Deactivation of appropriate Travelway Sections and Locations. Updating of any locations in the Travelway Location table, as needed.

h) Creation of a new node (e.g., due to addition of a new road), in the middle of a route, with a newly-determined measure: Creation of a new Travelway Location for the node. This would also involve creating a new Intersection.

12.9.10. What needs do you see for managing historical data, which are not currently being met? Desired functionality for historical data has been identified and accounted for in the system design. The logic for recreating historical conditions has been developed and tested, but has not yet been implemented in a general purpose application.

13. HPMS Submission

13.1. Have you developed a separate or modified LRS to meet HPMS submission requirements? If so, please elaborate. The HPMS submission is currently managed under the old system. This will be moved into the TMS database in Phase II.

14. Data Integration

14.1. Data transfer between information systems

14.1.1. Consider a roadway characteristic such as Average Annual Daily Traffic (AADT), which is typically used by many information systems. When new AADTs are determined, how are the new values transferred to other information systems (e.g., traffic modeling, bridges, railroad crossings, etc.)? Within TMS, all data are integrating through the relational database. For legacy systems, some information is transferred between systems using manual methods or custom routines.

Data are transferred from legacy systems to TMS by custom ‘interface’ routines. Data stored in the ‘old system’ or in non-standard referencing systems are converted ‘one way’ by a system of ‘cross-walk’ tables to the Travelways system (to the new county-based routes, which the Travelways system automatically
converts to the continuous route system). Different units are in the process of cleaning up their data to enable a smooth transition to the TMS.

Business rules for the 'old system' will be supported (e.g., generation of route log listings) until a cutoff date to be established in the future.

14.2. Integration of different LRSs

14.2.1. To what degree are your multiple LRSs integrated?

a) Are you able to translate measures from one LRS to another? The Travelways system is a single LRS that supports both continuous and county-based log units (linear referencing methods), integrated directly in the Travelway Location table. The county-based logs are calculated from the continuous logs by knowing the continuous log values at which Travelways enter and leave counties. In addition, the 'old system' routes are stored directly in the GIS base map as an Arc/Info route system, in addition to the Travelway route system. This facilitates conversion from legacy systems to the Travelway system.

b) Are you able to map features using different LRSs? Features can be mapped using the different linear referencing methods, if needed, using the common GIS base map.

c) Are you able to perform queries with custom applications, drawing from data sets using different LRSs? Legacy data, using the 'old system' linear referencing method, are first converted to the 'new' system as a common query environment. Within the Travelways system, a query could include specifications for both continuous and county-based log units.

d) Are you able to perform ad hoc queries, from data sets using different LRSs? Yes, for the different linear referencing methods, as described for the previous question.

14.2.2. What major problems and/or successes have you had integrating data located by different LRSs? The integration of legacy data by conversion to the common Travelways system is anticipated to be very successful. The process has identified some problems with the quality of some operational data sets, which data managers may be reluctant to rectify (since the data were of a quality that served their purposes).

14.3. Integration with GPS and other geographically referenced data

14.3.1. Are you integrating GPS data with linearly referenced data? If so, please elaborate. GPS data will be accepted for input to the Travelways system, but not in Phase I of the project.

14.3.2. Does your GIS base map have link attributes? If so, what are the attributes, and how are these integrated with linearly referenced data? N/A.

14.3.3. Are you integrating linearly referenced data with any point or polygon data (e.g., for any specific projects)? Linear data is being integrated with polygon data in building some of the data for the TMS database (using polygon events in Arc/Info). Linear and point data will be integrated with polygon data for analysis purposes.

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15. Use of Related Technologies

15.1. Describe any GPS activities related to linear referencing, such as:

15.1.1. Refinement of the LRS measures? No activity at this time.

15.1.2. Refinement of the GIS base map? No activity.

15.1.3. Resolution of discrepancies between the LRS and GIS base map? No activity.

15.1.4. Data collection? No activity directly affecting the Travelways system.

15.2. Describe any use of video logging, and the use of linear or other referencing systems for locating video footage. An interface will be developed for converting data collected by ARAN van into the Travelways system.

15.3. Describe any use of other technologies related to linear referencing:

15.3.1. Data warehousing: In some respects, the TMS enterprise database serves as a data warehouse for incorporated operational data sets.

15.3.2. Intelligent transportation systems (ITS): St. Louis and Kansas City are currently implementing ITS technology. The plan is to integrate their intelligent transportation systems with MoDOT’s LRS in the future.

15.3.3. Other:

16. Relationship to Other Modes of Transportation

16.1. Are you considering the use of linear referencing to support other modes of transportation, such as for supporting analysis and modeling of transit information? It is anticipated that other modes of transportation will be supported in a future phase.
APPENDIX F: 20-27(3) STAKEHOLDER GROUPS

Attendees of the NHCRP 20-27(3) Workshop on Functional Specifications for Multimodal, Multidimensional Transportation location Referencing Systems. December 3-5, 1998, Washington, DC. (One of the four expert panel or workshop meetings whose results were reviewed in this thesis).

Group 1: Transportation Planning, Highway Construction, and Asset Management

Ron Cihon, Coordinator
Washington DOT
Frederic Aubry
ESRI
Charles Fleming
Georgia DOT
Karl Olmstead
Minnesota DOT.
Roger Petzold, Project Panel
FHWA
Paul Scarponcini
Bentley Systems, Inc.

Teresa Adams, Recorder
University of Wisconsin-Madison
Stephen Bespalko
Sandia National Laboratories
John Hudson
Connecticut DOT
Thomas Palmerlee
Transportation Research Board
Thomas Ries, Project Panel
GeoAnalytics
Frank Winters
New York State DOT

Group 2: Highway Safety and Incident Management

Nancy Armentrout, Coordinator
Maine DOT
Bobby Harris
GIS/Trans, Ltd.
Tim Neuman
CH2M Hill
Kenneth Opiela
NCHRP Program Officer
Transportation Research Board

Al Butler, Recorder
Hamilton County, Tennessee
Charley Hickman
U.S. Geological Survey
Wende O’Neill
BTS - USDOT

Group 3: Traffic Management and Highway Operation

Val Noronha, Coordinator
NCGIA
Bill Cairns
Mitretek Systems
Steve Gordon
Oak Ridge National Laboratory
Fang Zhao
Florida International University

Tim Nyerges, Recorder
University of Washington
Kenneth Dueker, Project Panel
Portland State University
Manny Insignares
TransCore
Group 4. Transit Facilities and Operation; and Commercial Vehicles and Fleet Management

Jeff Orton, Coordinator
Utah Transit Authority
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APPENDIX G: REFLECTIVE PRACTITIONER LRS EXERCISE

An ugly baby is a very nasty object,
and the prettiest is frightful when undressed.

Queen Victoria

G1. Appendix Purpose

The purpose of the work summarized here is to:

1. Synthesis: Draw a synthesis on work carried out in the thesis as a whole
2. Future research: Point to the direction of possible improved LRS practices.

A broader goal of the work summarized here is to demonstrate some "reflective practitioner" contemplation of LRS. The research bases of the proposed approach laid out here are:

1. Thesis Research Findings: A review of the key research findings
2. Critical Success Factors (CSF): Developing a number of the main "reflections" on the research here into LRS "critical success factors", or determinants for the design of an improved framework for handling linear referencing issues.

As noted in Chapter/section 1.5 and Chapter/section 2.4 of this thesis, LRS as a whole has to date been the topic of little more formal or "framed" research before. At the outset of this particular research, the reality of this research situation had to be faced squarely. A primary goal was to attempt to provide a more fundamental basis of framing LRS research and understanding LRS itself. The work undertaken to this point will hopefully allow the field to have:

1. A firmer base of LRS reference
2. Support for selecting focus areas for more detailed and further LRS research.

G1.1 Reflective Practitioner

The work summarized here attempts to draw this into a set of 'reflective practitioner' framework for thinking about the further development of LRS practice and research. On reading many theses, it seems that 'reflection' is one thing that energy has relatively been left in shorter supply for at conclusion! The fuller development of these new topics and further development of the reflection here is unquestionably one or more doctoral theses in their own right. Additional research thesis it is suggested would:

1. Base development: More generally developing the area identified here, and
2. **Focused technical issues**: Deal with some of the more detailed technical issues addressed identified.

**G1.2 Research Adjunct**

This appendix attempts to demonstrate "reflective thinking" in action. In this sense this work was thus a vital part of the overall research frame of this thesis. However, it is also in some sense an adjunct to the main body of work that was carried out here. The work undertaken was included here as an appendix, as on fine balance it was felt to be an extension of the main work carried out in the thesis.

**G1.3 "One" Approach**

The method proposed here is *one* possible framework to a set of the main research LRS research issues and one set of field observations identified. The proposed framework does in some form address several of the key individual LRS issues identified in this thesis. The framework is developed to an initial, but not exhaustive, level through the development of a set of example artifacts and a short, worked example. The proposed high-level conceptual schema for LRS should be regarded as much for example. This would be in contrast to necessarily being the only formulation to that might work as a generic LRS framework or to handle a particular LRS working context.

The framework here is thus *one* conceptual approach to some of the technical issues discerned in this research. Clearly, the fuller exploration and exposition of the issues and the framework developed in initial form could not be undertaken without the base of the bulk of the research work that was carried out in this thesis. This exercise however does synthesize the work and suggest new directions forward.

The review provided here should be read in conjunction with Chapter/section 10.5.

**G2. Proposed LRS Schema Overview**

It was decided to design the conceptual basis for an improved framework that would at least broadly meet the key LRS requirements and observations listed in the Conclusions of this thesis (Chapter 10). As stated in the introduction to this chapter, this exercise was conducted more in the spirit of pulling together the observations gained from the heart of this thesis, rather than, starting a new series of research tasks or even a new thesis.

At a top-level, the framework developed reflected the notion that the major effective contribution of the Vonderohe model was the concepts of "anchor points" and "anchor sections". The addition of these concepts seems to go a long way in providing a simple mechanism for in short dealing with the issues of accuracy and relating map data (including LRS held data) at different map scales. The particular form of the Vonderohe model possibly offers a reasonable framework for highway authorities. However, it may be *too restrictive* model for other transportation modes and operations (as described in Chapter/section 5.2 and Chapter/section 8.6).
As a balancing contribution to the Vonderohe model, greater attention here was given to the flexibility of the model form. The key mandate provided in the CSF’s in the previous section was a flexible model form.

As used throughout this thesis, the term network has been used and may be defined as “a graph without two-dimensional objects or chains”. In this simplified exposition for a potentially improved conceptual framework, a network may be simply seen as a set of connected links.

At the highest level, the setup of LRS may be divided into four most fundamental network-based operations. These are:

1. Network Description: Basic Data on the network must be gathered.
2. Assignment to Network Components: The creation and set-up of the network components, on which the LRS is to be placed.
3. Route Creation: The creation of routes on the network, on which the LRS will operate.
4. LRM: The actual selection of the LRS method to be used within the route system.

The framework tentatively identified here focuses on the first three items, and in particular the second two. That is:

1. Network Description. A description of the network has to be gathered. In theory, this should be a relatively straight-forward exercise. In reality, there may be questions involving:
   a. Network Identification and Choice: Which network to use (for example, if different networks are in use within the jurisdiction, such a TIGER file, or, a GDT street network centerline file).
   b. Network Data: Such data, especially if locally generated, may not always be available in complete and consistent form. Intersections, links and other basic characteristics need to be clearly delineated.
   c. Network Cleaning: Depending on the exact results of the previous step, when significant errors exist, 80% of the total end work in projects, such as described here, typically are the initial cleaning of the network.

2. The Setup of Cartographic Elements. A LRS can only be placed on as detailed network as was originally created. If the highway intersections do not have ramps on them, they can of course only be displayed without ramps. The suggested approach here was then to create a sort of “highway Lego”. The analogy is to a number of areas where ‘a toolbox’ of more commonly used core parts is used to assemble a larger whole. Just one particular example is the UML diagramming language itself, where there a number (seven) of “tool-chests” of predefined diagrams types for constructing the (seven) main different classes of UML diagrams.

The wider advantage of constructing such a ‘highway Lego’ obviously goes beyond just potential LRS uses. It however in all cases includes the ability to pre-describe certain network characteristics and forms to recognize, and then standardize, highway types.
3. **Creation of Route Elements:** It was recorded (See Chapter 8) that routes across the various modal transportation sub-communities have many shapes and forms. It was thus decided to investigate the basis for the creation of more flexible route structures than for example allowed in other model forms that have been proposed (e.g., Dueker-Butler, 20-27-2, etc., as reviewed in Chapter 5).

Chapter/section 3.6 reviewed current best practice data modeling techniques. As a tool to facilitate such consideration, it was decided to use of an object-oriented methodology as a means of demonstrating the concepts suggested. The concepts outlined here readily appear to fit a OO methodology. However, the concepts are not dependent on it (as they could be expressed in other formats). This work proceeds by first evaluating the setup of network object classes (which could have wider utility than for LRS alone).

**G3. Network Cartographic Elements**

This section considers the definition of a number of example standard cartographic network types.

**G3.1 Justification**

A LRS “sits on top of” a network. This thesis has practically demonstrated (for example in, Chapter/section 6.6, as well as elsewhere) that the detail of transportation networks can occur in many forms. To better model (in terms of the expressed transportation information user communities), LRS we need to “better” model the physical networks. As considered in this thesis, “better” is considered here from a transportation user community or practitioner viewpoint. It includes allowance for the classes of network types that occur, and an increased ability to deal with real world “messiness” (such as earlier outlined in Chapter/section 3.2.1) occur with spatial data.

It is clear from the work carried out in this thesis that transportation is not one user community, but several (see Chapter/section 6.11 and Chapter 8). These information communities all conceive of networks differently, at various levels of use and aggregation. Attempt here has been made to synthesize a set of fundamental spatial network elements that have been recorded in this thesis as being either in use or of utility.

The framework provided below is a preliminary attempt to create an improved conceptual network / object-based structure for considering LRS. It is not, in its preliminary field form defined to a fully detailed operational level. The framework within the practitioner context of this thesis, uses a nomenclature of common transportation field parlance. This nomenclature does not for example exactly directly fit any one of the road data models so far described (though does it fit most of them, approximately, since they, at least to some degree share terms, as outlined in Chapter 5 and in Chapter 8). However, the terminology used does broadly fit the most common, in-field, use.

Describing a set of linear features serves the following two main goals:

1. **Network Coding:** It allows the description of generic physical forms that have a set of pre-described attributes associated with them. This will allow the facilitated encoding of particular network variations found in the field. There is
then a standard template for example for encoding a cloverleaf intersection. Once the core form of this intersection type is described, local variations of it may be readily adapted.

2. **LRS Support**: In particular, it then facilitates the tracing of LRS routes onto the network (for example, a LRS around a rotary or a cul-de-sac).

Right now, encoding of intersections is difficult for LRS in most circumstances they are used. The advantages of the framework proposed here become potentially much greater still once local roads are set-up for possible use with LRS. This is occurring with increasing commonness in many local agencies with highway or transportation responsibilities, such as MPO's (e.g., Delaware Regional Valley Planning Commission), Counties (e.g., Wayne County, GA) and cities (e.g., Bangor, Maine).

### G3.2 Selected Linear Features

The proposed initial set of linear features draws from the set used in the case studies as a base comparison set (see Chapter/section 6.6), with the addition of the 'simple link” and the addition of two other forms. They are:

1. Simple link  
2. Divided highway  
3. Ramps and approaches  
4. Non-contiguous traversals  
5. One-way pairs  
6. Cul-de-sac and Dead end street  
7. Layered or tiered roadways  
8. Proposed roadways.  
9. Associated facilities (e.g., truck runoffs, etc)  
10. Service roads (i.e., a linear feature with associated frontage road)

An example of potential more detailed network forms that might be encoded include “a linear feature with railroad crossing”.

The above by no means a fully exclusive set. It however covers the most significant types in common recognition in state DOT’s (as shown in Table 1 Real World Highway Features and Networks), as well as reviewed in the Case Studies (as reviewed in Chapter 6). Some further brief notes on the forms are included below.

Figure 77 gives an outline sketch of the proposed initial highway Lego” forms or components.
Figure 77 Simple Linear Features

1. Simple Link

2. Divided highway

3. Dead End Street

4. Cul-de-sac

5. Linear feature with associated frontage road

6. Linear Feature with Railroad Crossing
For each of the selected “Lego” elements, a brief description is given below.

1. **Simple Link Object**

   Simple links are already provided (typically to date in non OO format) in most COTS GIS software. Most simple links are bi-directional, and must be represented by a digraph.

   A simple link is shown in Figure 78.

   ![Figure 78: Simple Link Object](image)

   **Attributes:**
   - Name: Simple Link
   - Topology:
     - Start node
     - End node
   - Geometry:
     - Length
     - Time in existence

2. **Divided Highway**

   Divided highways have a central median, and thus may be represented by a very similar form as the simple link. Figure 79 provides an indicative divided highway object.

   ![Figure 79 Divided Highway Object](image)

   **Attributes:**
   - Name: Divided Highway Object
   - Topology:
     - Start node
     - End node
   - Geometry:
     - Width/type of central median
     - Length
     - Time in existence
   - Behavior:
     - Snap to link with same node
3. **Dead End Street**

Dead end streets are streets without a turn-around, and thus again may be very similar to simple streets. Figure 80 shows a Dead End Street object.

![Figure 80 Dead End Street Object](image)

<table>
<thead>
<tr>
<th><strong>Name:</strong> Dead End Street</th>
<th><strong>Attributes:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology:</td>
<td>Start node</td>
</tr>
<tr>
<td></td>
<td>End node</td>
</tr>
<tr>
<td></td>
<td>Length</td>
</tr>
<tr>
<td></td>
<td>Time period</td>
</tr>
</tbody>
</table>

| **Behavior:** | Snap to link with same node |

4. **Cul-de-sac**

Cul-de-sacs have turn-arounds. A standard convention needs to be applied whether the LRS goes clockwise or anticlockwise around the cul-de-sac. Figure 81 shows an indication of a cul-de-sac object. Fuller definition of a cul-de-sac could include the ability to specify it through a very few indicative measurements (such as length, and, radius of turn around).

![Figure 81. Cul-de-Sac Object](image)

<table>
<thead>
<tr>
<th><strong>Name:</strong> Cul-de-Sac</th>
<th><strong>Attributes:</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology:</td>
<td>Start node</td>
</tr>
<tr>
<td></td>
<td>End node</td>
</tr>
<tr>
<td>Geometry:</td>
<td>Length of link</td>
</tr>
<tr>
<td></td>
<td>Diameter of circle</td>
</tr>
<tr>
<td></td>
<td>Time period</td>
</tr>
</tbody>
</table>

| **Behavior:** | Snap to link with same node |

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5. Linear Feature with Associated Frontage Road

Some links have associated frontage roads which may all be associated together for example in one data maintenance route. The frontage road could be modeled in a number of ways — for example as its own separate link (and thence it sown ‘route’). However, sometimes data for frontage road is managed with the data for the route for the link with which the frontage road is associated. Figure 83 shows a linear feature with frontage road.

Figure 83 Linear Feature/Frontage Road

<table>
<thead>
<tr>
<th>Attributes:</th>
<th></th>
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</thead>
<tbody>
<tr>
<td>Topology:</td>
<td></td>
</tr>
<tr>
<td>Start node</td>
<td></td>
</tr>
<tr>
<td>End node</td>
<td></td>
</tr>
<tr>
<td>Geometry:</td>
<td></td>
</tr>
<tr>
<td>Length of link</td>
<td></td>
</tr>
<tr>
<td>Length of frontage road</td>
<td></td>
</tr>
<tr>
<td>Time period</td>
<td></td>
</tr>
</tbody>
</table>

Behavior:
Snap to link with same node

6. Linear Feature with Railroad Crossing

Links with railroads crossings have certain characteristics (such as presence of gates, number of tracks, etc). These also may be encoded in a standard format.

Figure 84 Link With Railroad Crossing Object

<table>
<thead>
<tr>
<th>Attributes:</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Topology:</td>
<td></td>
</tr>
<tr>
<td>Start node</td>
<td></td>
</tr>
<tr>
<td>End node</td>
<td></td>
</tr>
<tr>
<td>Geometry:</td>
<td></td>
</tr>
<tr>
<td>Length of link</td>
<td></td>
</tr>
<tr>
<td>Number of tracks, etc</td>
<td></td>
</tr>
<tr>
<td>Time period</td>
<td></td>
</tr>
</tbody>
</table>

Behavior:
Snap to link with same node
G3.3 Intersections

Within the Case Studies carried out within this thesis, different traversal forms that were encountered were reviewed (see Chapter/section 6.6). Rotaries were included in that review, but not explicitly other intersection types that commonly exist. Similarly as for highway components, a set of intersection forms can be modeled. The coding of intersections becomes more important as Local Roads are considered and improved coding accuracy is sought. The meeting these two requirements was identified as CSF for an improved framework for dealing with LRS. A brief review is given below.

The intersection types selected here as base types are:

1. Basic Node
2. T-Junction
3. Simple Cross-roads
4. Basic Rotary
5. At-Grade intersection
6. Cloverleaf intersection.

Figure 86 and Figure 87 shows these basic forms diagrammatically.

Figure 88 provides an outline of data that might be provided as a sample intersection description.

**Figure 85: Sample Intersection Type**
Figure 86 Intersection Types

1. Basic Node
2. T-Junction
3. Simple Cross-roads
4. Basic Rotary
5. At Grade Intersection
Indicative detail is provided here is for what may be regarded more generally as the most complex intersection type (that is, a cloverleaf intersection). In Figure 87 above, a box at the intersection of lines assumes the placement of a connection node. That is, where a box is not provided at an intersection, there is no connection and the lines represent transportation network components that are “grade-separated”.

In the following example, as with all the other examples provided here, the indicative detail is provided would need to be substantially developed in any development of this approach. Complex intersections would benefit from a higher degree of specification than an ordinary intersection, but also benefit from the development of standardized approaches for dealing with common issues. For example, the definition of what is “east”, “west” needs a convention to define it. (Note: What is running locally west-east, may be part of route system which is over its course is running principally north-south). It is not logically difficult to put direction-naming conventions in place (many exist in DOTs today), but such formalisms need to be developed, clearly specified and adopted.

Figure 88 shows an indicative cloverleaf intersection object.
G4. Route or Traversal Construction

This section considers a more flexible framework for the construction of network-based routes.

G4.1 Outline Definition of Route Elements

Routes may also be called “polylines”, “traversals” or “longitudinal features” (see Chapter/section 4.2). For this simplified presentation we just call these entities, “routes”. This term is in common field parlance and understanding. However, it is also confusing to some as it is also in common parlance for different transportation needs. The term “traversal” may appear to carry less baggage – but it also has less sense of common understanding and carries less sense of identity and association that that the term route implies.

Routes are made up linear features. Routes may also themselves be elements of other linear features. Examination of the Case Studies carried out in this thesis and the wider LRS field review, indicated that a basic set of “route entities” are more commonly used. The following set of five most basic linear terms have been adopted for the following simplified conceptual exposition:

1. **Segment.** The smallest network atomic piece. Here it is assumed to be a straight line between two points that have positional data associated with them (a definition could be allowed that allowed segments to be curved, without greatly affecting the overall schema here. The points are not topological nodes.
2. **Links.** A line between two nodes. It may be made of one or more segments. Where not comprising of multiple segments, a segments may comprise of just one segment.

3. **Section.** A collection of segments or links. A section may be less than one topological arc (or link), or cover many links (including up to two partial links).

4. **Route.** (Otherwise called a polyline or traversal elsewhere in this thesis). A collection of connected segments, links or sections.

5. **Additional route feature.** These are listed below in the next section.

6. **Network.** A set of connected links.

For the purpose of the exposition here, the greater focus is perhaps first on the general form of the overall hierarchy, rather than, the exact naming or delineation of sub-elements. The set of sub-elements identified is believed to be relatively rich enough to cover most of the network modeling needs identified within the transportation information communities identified within this thesis. However, certain elements may need adding to meet the needs of certain user sub-groups. For example, in Chapter 7, it was recorded that transit operators used many variations of an individual main route. Therefore in addition to those elements above, the following may be added. These include additional sub-components of routes and higher order route and network elements:

7. **“Sub-routes”:** These are parts of routes.
8. **“Super routes”:** These comprise of contiguous routes or an aggregation of routes.
9. **“Meta routes” or “Annotated Routes”:** These comprise of routes with associated route features. It can for example be a route with the various route associated appendages and facilities, e.g., 195 and 1295, rest stops, truck run-offs, etc.
10. **Route systems:** A set of routes on one network.

Thus, with the base network elements proposed above and with the additional route classes, a ten level hierarchy may be created.

### G4.2 Additional Route Features

Additional Route features (item 5 above) may comprise for example of:

1. Ramps
2. Truck run-offs
3. Rest areas
4. Spurs
5. Associated Route elements (e.g., 195, 1195, 1295, etc)
6. Alternate routings
7. Other route associated features.

Figure 89 below shows a generic object class definition for the above example route feature classes.
G4.3 Fuller Definition of Route Elements

A network schema was sought that would meet the basis for LRS indicated by the field-work carried out for this thesis (and as summarized in Table 59 above). On the bases of this research, the following general network schema is proposed both for wider use but in particular with the set-up of LRS.

1. Segment. This is currently here defined as, "the smallest entity of network infrastructure". It may be defined as unit over which begin and end positional data are stored. That is, there is at least a begin and end x,y. This data may be field-recorded data, or, of necessary in certain circumstances, positionally inferred relative data. At least relative position may be approximately inferred by routines that execute calculation based on knowledge of higher-order network elements. For example, if a segment is one of three segments that make up a link, and the begin and end points of the link are known "very" accurately, and the GPS recording vehicle has recorded three inflexion points a segment begin and end x,y position may be calculated.

Each segment as here defined records that begin and end segments it is attached to. As no intermediate positional data is recorded between the begin and the end points, the alignment is assumed to be straight between the segments. As an alternative, intermediate data points may be stored. However, there appears to be some field utility for at least some applications in at least having available in the transportation network tool-chest a fundamental element or entity between which no other positional data is formally recorded, apart from end points. (This might
be useful for example defining traversals where key location data measurements have been recorded at discrete intervals. For example, a vehicle-based videolog camera may take shots at every 1/100th mile and have a straight line highway segment may be recorded to be associated with this image.

In such cases, the boundary segment case is where a segment is attached to a topological node. A review of present technology, in particular GPS data collection in Chapter/section 4.5.1, indicates that segment positional end data may in field practice typically be available on:

1. Standardized distances, by automated data collection devices (e.g., Arran vans) every 0.01 mile (17.6 yards), or 0.001 mile (1.76 yards)
2. Distances set by other criteria, e.g., change in surface condition
3. From historical or legacy data.

The positional data available with segments may be relative or less accurate than say typically associated with anchor points (see Chapter/section 5.2).

Other terms may be used rather than “segment” – for example, sometimes “segment” and “section” are used interchangeably in some DOT’s.

Many DOT’s for data management purposes have divided their highways up into fixed lengths segments (sometimes called by them, “sections”), such as 0.01 miles in length. However, the implied sense here is that positional data is available, which there may not necessary be for fixed length data management schema. The proposed indicative object class form of the segment is shown below in Figure 90. The object descriptions provided below by feature may be referred to as “objects”. However, they are in fact class descriptions. As described in Chapter/section 3.6, an individual instantiation of the class is a (single) object. An instantiation of the class description for “highway segment 331” creates an object that for example:

A: General Class Properties: Inherits all the properties common to class “segment”. For example, segment 331 must be:
   i. Connected adjacent segments or a node
   ii. Have end point coordinate properties
   iii. Instantiated with the properties of the route they are on

and,

B: Specific Instantiation: Gains all the class relevant properties of segment 331. For example, segments 331 must inherit:
   iv. Route 3 properties, because it is on Route 3
   v. Network x properties, because it is a part of network x.

The framework must allow certain properties to be overridden in values, for example, the local street name characteristic. For example, segment 331 may by inheritance from say the sub-route it is on be called “The Baltimore Pike”, but within three predefined links it is called “Main Street”. Other properties may be set either locally, regionally, globally (or even at the very highest-level, system level) as “inviolate”. Certain of the basic physical properties of segments may be inviolate (for example, system level, topological connection to another segment or node) as well as locally set (for example, “segments in this area may not cross over the county boundary”).

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The begin and end x, y above may be defined in latitude/longitude, a state plane coordinate system, NAP specification, and include various measures of data quality that reflect the “messy” nature of spatial data (as briefly reviewed in Chapter/section 3.2).

The topology attributes defined above may be defined a priori (for example, segment 101 must connect to segment 102) or may be calculated and instantiated, “on the fly”.

2. Node: It is defined in the Glossary, (see, Appendix A), of this thesis as, “a zero-dimensional object that is a topological junction between two or more links, or an end point of a link”. Nodes are different from Anchor Points as they are, first, topological connection points. Anchor points are defined as, “zero-dimensional location that can be uniquely identified in the real world in such a way that its position can be determined and recovered in the field”. Anchor points will often have topological information associated with the location, but as indicated in Chapter 5, this will not always be the case. Nodes as defined here will have positional information associated with them, as they are the end of a segment. A object description of a node is given below in Figure 91.
3. **Link.** This is strictly defined as, "the topological connection between two ordered nodes". In topological or graph theory terms, it would be called an arc or an edge (if unidirectional). The Glossary defines a link as, "a one-dimensional object that is a topological connection between two nodes". However, in common parlance and use in state DOTs, such as visited in the case studies, the term 'link' often refers as well to the linear feature that connects two nodes in a GIS centerline layer. If working rigorously here a clear distinction should be made for data modeling that a 'link' is simply a topological connection, and a 'line' has shape and position and can be used for cartographic representation. However, reflecting we use the term “link” in this proposed schema, reflecting our case study experience described in Chapters 6.

A “link” as here defined may be potentially made up of many hundreds or thousands of segments, or just one. In some schema ‘sections’ may be less than one link in length. For example, in the case studies, PennDOT’s RMS had sometimes several hundred “segments” (in their parlance “sections”) between topological nodes (intersections), defining links, on the Pennsylvania Turnpike. While wishing in this schema to retain the greatest degree of flexibility, it was felt useful to make a minimally clear distinction between sub-link topological highway elements and those that are above “link” in the hierarchy. Figure 92 provides the summary object description.

**Figure 92 Link Object Description**

<table>
<thead>
<tr>
<th>Name: Link</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attributes:</td>
</tr>
<tr>
<td>Geometry: Begin x,y End x,y</td>
</tr>
<tr>
<td>Topology: Connected node A Connected to node B</td>
</tr>
<tr>
<td>Comprises of: List of segments</td>
</tr>
<tr>
<td>Metadata: Time period: Descriptive Data:</td>
</tr>
<tr>
<td>Behavior: Connect to node A Connect to node B</td>
</tr>
</tbody>
</table>

In the link object description above, the *begin* and *end* x,y may under one scenario be instantiated as necessary, and just the link ID stored. However, in setting up a general framework, some overhead may be taken in allowing database object place locations for some applications that require them. Agencies are likley only to want to set up one foundation network and it will need to flexible to the needs of a variety of purposes. For example, some network modeling applications may require ready access to link coordinates. In transportation applications, a design decision would have to made across many such items which ones were truly generic enough to merit inclusion in the core framework model.

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4. **Section.** It is defined in the Glossary as, "An ambiguous term that generally refers to a section of roadway between major roadway features (e.g., intersections)". In the context of dynamic segmentation in GIS, a traversal may be comprised of sections, each of which corresponds to one link or a portion of a link, directed along the link with specified from and to measures”.

The definition used within the hierarchical schema proposed here, is that a section is a **supra-link collection of segments**. This definition could be readily relaxed to define a section as any collection of segments, including at the sub-link assemblage level. It is possible that an intermediate term could be introduced to define a sub-link collection of “segments”. While a term is not immediately forthcoming from the field-work conducted, it could be for example called a “**super segment**” or a “**link portion**”.

One reason for sections between link and route is in short to provide a convenience to the real world and to facilitate data management activities. A section corresponds to the physical entity for which much real world highway data management and maintenance occurs. That is, highway departments manage highway (“control”) sections. These more typically correspond to the way that the highway was constructed (i.e., pavement construction and thence maintenance sections) and may have very little correspondence to the topological network (which may in any event have been added to and altered since the highway sections were created, with additional curb-cuts and side streets, etc.).

Sections as defined here are very analogous to segments. They may possibly be defined as being made up of:

- Just segments
- Segments and links
- Segments, links (and, perhaps, other sections).

In the latter case, it may be decided that generally a class may not be made up of members of it’s own class. However, there are cases where the flexibility to code such may potentially occur. For one possible example, bus route sections on bus route 89, may actually comprise of sections that are already defined for bus route 79. The distinction at least here is that they are sections are common and equivalent, and have been predefined on another route.

Figure 93 provides a summary description of the section object.
7. **Sub-Route**

These are defined as being part of a route. They may be defined as being a whole number of either links or sections that make up a route (see Figure 94).

8. **Route**

Routes as defined here are perhaps the most fundamental unit. The outline description is provided in Figure 95.
9. **Super-Route**

These objects comprise contiguous routes or an aggregation of routes. They may also be an agglomeration of sub-routes or sub-routes and routes (see Figure 96). Their potential creation is again in large part a data management convenience from the field practitioner's viewpoint, in particular for corridor analysis. When managing or analyzing the I95 Corridor, this entity would be a collection of the I195 spurs and the I295 parallel routes. Such an agglomeration could always be created in bespoke fashion on the fly to meet particular transportation application needs. However, the creation of a standard object to allow the more direct management of this occurrence, has at least the following two distinct advantages:

1. **Coding Lessons:** It allows coding lessons to be shared across modes. For example, what experience learnt putting in place a super route for the I95 Corridor Coalition would be useful for a bus operator managing a set of routes that broadly go under the name 'Bus Route 69' to Hanscom AFB?

2. **Data Maintenance:** There are likely to be various data management and maintenance routines that would commonly be support such a object class. (Their detailed specification is beyond the scope of this initial higher-level conceptual framework).
Figure 96 Super-Route Description

<table>
<thead>
<tr>
<th>Name: Super-Route</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attributes:</td>
</tr>
<tr>
<td>Definition:</td>
</tr>
<tr>
<td>Geometry:</td>
</tr>
<tr>
<td>Infer, begin, end and component x, y</td>
</tr>
<tr>
<td>Topology:</td>
</tr>
<tr>
<td>Connected to segment, link section A</td>
</tr>
<tr>
<td>Connected to segment, link, or section B</td>
</tr>
<tr>
<td>Comprises of:</td>
</tr>
<tr>
<td>List of segments, links, sections</td>
</tr>
<tr>
<td>Metadata:</td>
</tr>
<tr>
<td>Time Period</td>
</tr>
<tr>
<td>Descriptive Data:</td>
</tr>
<tr>
<td>Behavior:</td>
</tr>
<tr>
<td>Connect to segment, link, section A</td>
</tr>
<tr>
<td>Connect to segment, link, section B</td>
</tr>
</tbody>
</table>

7. Meta-Route

These comprise of routes with associated route features. It can be a route with the various route associated appendages and facilities, e.g., 195 and 1295, rest stops, truck run-offs, etc. (see Figure 97). A perfectly reasonable conceptualization of this would be “a route with some sub-components expanded”. However, in another view, the “associated facilities” that belongs or associate to a route may be in data management terms may contain several orders of magnitude of data (and complexity) than exist with the route structure itself. Thus, the conceptualization of the meta-route be a higher-order (or containing ultimately more data) maybe more appropriate.

Figure 97 MetaRoute Description

<table>
<thead>
<tr>
<th>Name: MetaRoute</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attributes:</td>
</tr>
<tr>
<td>Definition:</td>
</tr>
<tr>
<td>Geometry:</td>
</tr>
<tr>
<td>Infer, begin, end and component x, y</td>
</tr>
<tr>
<td>Topology:</td>
</tr>
<tr>
<td>Connected to segment, link section A</td>
</tr>
<tr>
<td>Connected to segment, link, or section B</td>
</tr>
<tr>
<td>Comprises of:</td>
</tr>
<tr>
<td>List of segments, links, sections</td>
</tr>
<tr>
<td>Metadata:</td>
</tr>
<tr>
<td>Time Period</td>
</tr>
<tr>
<td>Descriptive Data:</td>
</tr>
<tr>
<td>Behavior:</td>
</tr>
<tr>
<td>Connect to route, meta route A</td>
</tr>
<tr>
<td>Connect to route, meta route B</td>
</tr>
</tbody>
</table>
8. Route System

It is defined as a set of routes on one network (see Figure 98). (The term network was originally considered in Chapter/section 1.3.1 and reviewed for this use of this conceptual framework briefly in Chapter/section 0).

**Figure 98 Route System Description**

<table>
<thead>
<tr>
<th>Name: Route System</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Attributes:</strong></td>
</tr>
<tr>
<td>Definition:</td>
</tr>
<tr>
<td>Geometry:</td>
</tr>
<tr>
<td>Infer, begin, end and component x, y</td>
</tr>
<tr>
<td>Topology:</td>
</tr>
<tr>
<td>Connected to segment, link section A</td>
</tr>
<tr>
<td>Connected to segment, link, or section B</td>
</tr>
<tr>
<td>Comprises of:</td>
</tr>
<tr>
<td>List of segments, links, sections</td>
</tr>
<tr>
<td>Metadata:</td>
</tr>
<tr>
<td>Time Period</td>
</tr>
<tr>
<td>Descriptive Data:</td>
</tr>
<tr>
<td><strong>Behavior:</strong></td>
</tr>
<tr>
<td>Add route</td>
</tr>
<tr>
<td>Delete route</td>
</tr>
</tbody>
</table>

9. **SuperNetwork**

It is defined as “a collection of networks” (see Figure 99). (The term ‘network’ was referenced above, under ‘Route System’). As networks have been considered in this thesis, a SuperNetwork could for example be the addition of two sets of connected links, such as the addition of the “base served bus network” with “the additional bus services network”. It could also include the integration of say a state road network with a local road network.

As such networks are likely in the field to have links in common, a process of *Network Conflation or network integration* has to be gone through. Network Conflation was a particular parallel research focus of the author, over a three-year period. It was earlier very briefly reviewed in this thesis, Chapter/section 4.4.4.

However, for the purposes of the simplified exposition here on an improved LRS framework, it will assumed here that a SuperNetwork is made of non-duplicative network links. This situation is only likely to occur where two networks were originally created from one “mother” network and not since modified.
Figure 99 SuperNetwork Description

<table>
<thead>
<tr>
<th>Name: SuperNetwork</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attributes:</td>
</tr>
<tr>
<td>Definition:</td>
</tr>
<tr>
<td>Geometry:</td>
</tr>
<tr>
<td>Infer, begin, end and component x, y</td>
</tr>
<tr>
<td>Topology:</td>
</tr>
<tr>
<td>Connected to segment, link section A</td>
</tr>
<tr>
<td>Connected to segment, link, or section B</td>
</tr>
<tr>
<td>Comprises of:</td>
</tr>
<tr>
<td>List of segments, links, sections</td>
</tr>
<tr>
<td>Metadata:</td>
</tr>
<tr>
<td>Time Period</td>
</tr>
<tr>
<td>Descriptive Data:</td>
</tr>
<tr>
<td>Behavior:</td>
</tr>
<tr>
<td>Remove network</td>
</tr>
<tr>
<td>Add network</td>
</tr>
</tbody>
</table>

Two points of clarification may be noted at the outset on all the above elements:

a. Positional informational is indicated for brevity by “x”. This may in fact be x,y,z (latitude, longitude, and elevation, within say WGS84).

b. As described is available in object methodology in Chapter/section 3.6.5, all of the objects may inherit appropriate attributes and information from higher order objects. For example, all elements that comprise:

   i. A route inherits the characteristics of the network, e.g., network metadata, the name or the network, etc.
   ii. A section may inherit characteristics of a route, e.g., “I am segment object number 331 and bus route 33 with these characteristics traverses me”.

Table 62 provides a brief summary of the network objects and the research basis for their justification. This set of objects appears to critically reflect three perceived sets of research criteria:

1. **Real World Field Use**: Meet the level of richness or level of diversity to fit the level of features found in field practice (as for example, originally laid out in Table 1 Real World Highway Features and Networks, which was drawn from CalTrans sources).

2. **Parallel Model Development**: To meet and then improve on the level of disaggregation recorded in the other transportation network/LRS models.

3. **Case Studies**: The detailed set of requirements discerned from the LRS Case Studies
Table 62 Network Objects: Summary Use and Justification

<table>
<thead>
<tr>
<th>FEATURE</th>
<th>USE</th>
<th>THESIS RESEARCH JUSTIFICATION BASIS</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Segment</td>
<td>Minimum sub-link length data stored for</td>
</tr>
<tr>
<td>2</td>
<td>Node</td>
<td>Basic topological point</td>
</tr>
<tr>
<td>3</td>
<td>Link</td>
<td>Basic node connector</td>
</tr>
<tr>
<td>4</td>
<td>Section</td>
<td>Often corresponds to a data storage length</td>
</tr>
<tr>
<td>5</td>
<td>Sub-route</td>
<td>Used in transit routes, maintenance routes,</td>
</tr>
<tr>
<td>6</td>
<td>Super-route</td>
<td>Used in transit; truck and other vehicular</td>
</tr>
<tr>
<td>7</td>
<td>Meta-route</td>
<td>Used to manage corridors, such as the '195</td>
</tr>
<tr>
<td>8</td>
<td>Network</td>
<td>Basic aggregation unit</td>
</tr>
<tr>
<td>9</td>
<td>Super network</td>
<td>Transit area basic unit of service;</td>
</tr>
<tr>
<td>10</td>
<td>LRS</td>
<td>Fundamental</td>
</tr>
</tbody>
</table>

G4.4 Route Feature Hierarchy

A composition matrix may be constructed of the various network route-based compositions that may be possible. From the work carried out in this thesis an attempt has been made to reflect the practitioner community input.

Table 63 Network Element Composition Matrix: Most General

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composed of:</td>
<td>Segment</td>
<td>Link</td>
<td>Sections</td>
<td>Sub-routes</td>
<td>Routes</td>
<td>Super routes</td>
<td>Meta routes</td>
<td>Networks</td>
<td>Super networks</td>
</tr>
<tr>
<td>1</td>
<td>Segment</td>
<td>X</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>2</td>
<td>Link</td>
<td>X</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>3</td>
<td>Sections</td>
<td>X</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>4</td>
<td>Sub-routes</td>
<td>X</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>5</td>
<td>Routes</td>
<td>X</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>6</td>
<td>Superroutes</td>
<td>X</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>7</td>
<td>Metaroutes</td>
<td>X</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>8</td>
<td>Networks</td>
<td>X</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>9</td>
<td>SuperNetworks</td>
<td>X</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
</tbody>
</table>

'x': elements on the column headings may be composed of items in the row headings indicated.

The above table says at the highest level the following:

Explicit choices need to be made (in each transportation community sub-domain) about the aggregation hierarchies that may exist in network route element construction.
The design choices include choices of whether high-order elements may be made up of:

1. Elements at its own level (e.g., “a route is comprised of routes”)
2. Elements may be made of more than one sub-element type at the same time (e.g., “a route may be made up of sub-routes and sections”).
3. All elements lower than it in the hierarchy.

Table 63, as currently filled out, would indicate that nearly all higher-order network elements may be constructed from lower order network elements. The case studies results and cross-model analysis carried out in this thesis, reflecting the interests of the broader transportation information communities, would indicate that this is in fact a reasonable, first order, working assumption. For example:

A section, may be made up of a Segment, Link or Section.

Alternatives structuring rules exist. It might be stated that a higher order network form may only be made up of units at a lower level in the hierarchy (and, perhaps only from a proscribed set). This would imply that the higher order units can only be composed of units that have been defined at a lower level (perhaps the next lower level) in the hierarchy.

An alternative more restrictive approach, but following some of the basic field experience gained in this thesis (Chapter 6), would be that a higher order network elements can only be made up of:

1. Elements at a lower level in the hierarchy, not at its own level (e.g., “Routes may not be made up of routes”).
2. One type of network sub-element within one setting or instantiation (e.g, “For this network, routes may only be made up of, say, sections”).
3. The selected sub-element can only be selected from the three immediately below it in the hierarchy (e.g., “Routes can be comprised of either sub-routes, or sections, or, links). The exception t this is networks which may comprise of all sub-entities.

Such considerations would lead to be more restricted table of composition, such as shown in Table 64.

Table 64 Network Element Composition Matrix: More Restrictive

<table>
<thead>
<tr>
<th>ELEMENT</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
<th>7</th>
<th>8</th>
<th>9</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composed of:</td>
<td>Segment</td>
<td>Link</td>
<td>Sections</td>
<td>Sub-routes</td>
<td>Routes</td>
<td>Super routes</td>
<td>Meta routes</td>
<td>Networks</td>
<td>Super networks</td>
</tr>
<tr>
<td>1 Segment</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>2 Link</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>3 Sections</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
</tr>
<tr>
<td>4 Sub-routes</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5 Routes</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>6 Super routes</td>
<td></td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>7 Metaroutes</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>8 Networks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>9 SuperNetworks</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
'x': elements on the column headings may be composed of items in the row headings indicated.

Again, it should be emphasized that the selected network element above strongly reflect those identified in the various research activities carried out for this thesis. Their use would appear to cover the vast majority of cases surveyed here. However, they are not exclusive. Other intermediate network intermediate types could however be potentially defined. For example, these may include:

1. A “route set”. This is commonly used by transit operators, but was not explicitly defined above.
2. Sub-segment. A part of a segment (as defined above).
3. Super link. A collection of more than one whole links.

**G4.5 “Network Element”**

The major criticism of the above approach may be that it is “too disaggregate”. An alternate approach is to recognize that there is a pattern in many of the objects created. That is, segments, lines, sections, sub-routes, routes, super routes, etc., have more in common than they have apart. These similar characteristics include:

1. They are linear features
2. They include topological connectivity information
3. They contain or may contain positional data
4. The inherit network characteristics.

By creating the class object “network element” allows greater flexibility in the creation of different network elements in different transportation information sub-communities application areas.

A network class object is shown below in Figure 100. Similarly, a standard network sub-element could be created, as shown in Figure 101.

**Figure 100 Network Element Class Object**

<table>
<thead>
<tr>
<th>Name: Network Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attributes:</td>
</tr>
<tr>
<td>Topology:</td>
</tr>
<tr>
<td>- Connected to network element A</td>
</tr>
<tr>
<td>- Connected to network element B</td>
</tr>
<tr>
<td>Comprises of:</td>
</tr>
<tr>
<td>- Defined network sub-elements</td>
</tr>
<tr>
<td>Geometry:</td>
</tr>
<tr>
<td>- Infer, begin, end and component x, y</td>
</tr>
<tr>
<td>Metadata:</td>
</tr>
<tr>
<td>Descriptive Data:</td>
</tr>
<tr>
<td>Behavior:</td>
</tr>
<tr>
<td>- Connect to network element A</td>
</tr>
<tr>
<td>- Connect to network element B</td>
</tr>
</tbody>
</table>
Figure 101  Network Sub-elements Object Class

<table>
<thead>
<tr>
<th>Name: Network Sub-Element</th>
</tr>
</thead>
<tbody>
<tr>
<td>Attributes:</td>
</tr>
<tr>
<td>Topology:</td>
</tr>
<tr>
<td>Connected to network sub-element A</td>
</tr>
<tr>
<td>Connected to network sub-element B</td>
</tr>
<tr>
<td>Comprises of:</td>
</tr>
<tr>
<td>Defined network sub-elements</td>
</tr>
<tr>
<td>Geometry:</td>
</tr>
<tr>
<td>Infer, begin, end and component x, y</td>
</tr>
<tr>
<td>Metadata:</td>
</tr>
<tr>
<td>Descriptive Data:</td>
</tr>
<tr>
<td>Behavior:</td>
</tr>
<tr>
<td>Connect to network element A</td>
</tr>
<tr>
<td>Connect to network element B</td>
</tr>
</tbody>
</table>

G 4.6  Route Elements Conceptual Data Model

A new conceptual data model for transportation network elements is shown in Figure 102. This diagram was produced in UML (as justified as current best practice data modeling, as described in, Chapter/section 3.6.6).

The data model and diagram reflect the following key technical summary points:

1. **UML:** The diagram is a UML Static Class diagram. There are seven UML class diagrams, but this is the appropriate one for the current exercise.

2. **Singular Networks:** It is assumed here in this initial formulation that a network element may only belong to one network. This assumption could possibly be relaxed, though probably only under described circumstances.

3. **Example Route Elements:** Not all the network entities earlier described are included, with some of the variations of route left out. The majority of the route types are included.

4. **Hierarchy Flexibility:** The data model reflects the hierarchical and flexible network objects created in the previous section. It allows for the flexible network aggregation called for by meeting the needs of a broader set of transportation information communities. Thus, it presumes that if a model is to be truly, generic it must also provide for flexibility in use. Higher order networks components are constructible from most lower order elements.

5. **The model reflects that networks as seen here are most fundamentally seen as comprising of “links”**.
6. In data modeling terms, “associations” between object classes are shown as “general associations”, rather than the tighter associations provided for in UML, that is, aggregations and compositions. This modeling decision reflects the fact the association between network and network elements is seen here in many cases is one out of several alternatives. (For example, a car may normally have 4 wheels, but, here a network may have always have links – that is, composition – but it may not have routes or sections).

7. There is a typical criticism that in much early data modeling work that often “everything is connected to everything”. That could be argued to be to a degree is true here. However, it also closely reflects the clearly expressed field experience and wider transportation information community CSF (summarized in Chapter/section 10.5.2). That is, the transportation community as a whole can be found to not only wish for, but actually be constructing networks, in a large variety of ways, as represented in this diagram, to meet their operational field needs.

In short, the purpose of the model form shown here is to allow the number of combinations that are in use. It also reflects that not all cases are equal likely. In effect, Figure 102 is the UML diagrammatic form of the information contained in Table 63 and Table 64.

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Figure 102 Proposed General Network Conceptual Model

Figure

Proposed General Network Conceptual Model

Network
- Geometry
- Topology
- Metadata
  - Time period
- Update()
- Aggregate()
- Simplify()
- Conflate()

LRS
- LRM method
- Routes
- Time Period
- Other Attributes
- UASC(): LRS

Super Routes
- Definition
  - G.T.M
  - Time period
  - Other Attributes
- UASC()

Routes
- Definition
  - G.T.M
  - Time period
  - Other Attributes
- UASC()

Sections
- Definition
  - G.T.M
  - Time Period
  - Other Attributes
- UASC()

Links
- Definition
  - G.T.M
  - Time period
  - Other Attributes
- UASC()

Segments
- Definition
  - G.T.M
  - Time Period
  - Other Attributes
- UASC()
Figure 103 Network Definition Pattern

Network Element Class 1 ("Route")
- Definition
- G.T.M.
- Time Period
- Other Attributes
+ U.A.S.C()
G5. The Very Simple Case Study Network

The framework proposed in this chapter, (Chapter/section 0), requires a preliminary step of assembling data on the network to be routed and to be assigned LRS. The steps to be completed in total are:

1. Network description
2. Assignment to Cartographic Classes
3. Route Creation
4. LRM.

G5.1 Network Description

A simple network is shown in Figure 104. It presumes as earlier described that a network selection and data cleaning exercise has been undertaken. The figure shows a simple network with two routes on it. Even on a very small example network as shown here there is a reasonable amount of data to manage.

The figure shows that the network contains the following features:

1. **Segments**: Segments are identified by triangles at the ends. One link has three segments (i.e., link 17). If a link is defined as having at least one segment, there are then 11 links with just one segment. There are thus a total of 14 (11 plus 3) segments.
2. **Nodes**: They are identified by small squares. There are 10 (i.e., n1 to n10)
3. **Links**: In this diagram they are identified by straight lines with squares at the end. There are 12 (i.e., l1 to l12).
4. **Sections**: None are shown or existing on this current network.
5. **Network**: There is one network here.
6. **Routes**: There are two routes or traversals, one identified by a (red) striped line, the other by a (green) dotted line.

There are no ‘higher-order’ network related objects such as SuperRoutes, etc.

---

14 *** ERROR: The top triangle should be further down the link (SEG 3)
It was described in Chapter/section 10.5.5, that checks may have to be done for data quality and completeness. One data quality check is for connectivity. There should be no “island” links (as the operational definition of a network is asset of connected links). One way to check for connectivity is to run “connectivity checker” (for example, a shortest path or other route finding algorithm which operates from every node to every other node on the network) to ensure full network connectivity. The link-node connectivity matrix (which some network connectivity checkers require) is shown in Table 65 for the data in Figure 104.
Table 65 Link-node Connectivity

<table>
<thead>
<tr>
<th>LINK</th>
<th>Start node</th>
<th>End node</th>
</tr>
</thead>
<tbody>
<tr>
<td>L1</td>
<td>N1</td>
<td>N7</td>
</tr>
<tr>
<td>L2</td>
<td>N2</td>
<td>N5</td>
</tr>
<tr>
<td>L3</td>
<td>N7</td>
<td>N8</td>
</tr>
<tr>
<td>L4</td>
<td>N5</td>
<td>N6</td>
</tr>
<tr>
<td>L5</td>
<td>N8</td>
<td>N11</td>
</tr>
<tr>
<td>L6</td>
<td>N6</td>
<td>N12</td>
</tr>
<tr>
<td>L7</td>
<td>N3</td>
<td>N5</td>
</tr>
<tr>
<td>L8</td>
<td>N4</td>
<td>N6</td>
</tr>
<tr>
<td>L9</td>
<td>N7</td>
<td>N9</td>
</tr>
<tr>
<td>L10</td>
<td>N8</td>
<td>N10</td>
</tr>
</tbody>
</table>

Other tables prepared for connectivity checking may also include for example a “node connectivity” table.

G5.2 Assignment to Cartographic Classes

The next step to assign network elements to the predefined set of cartographic or network map elements. Using the draft classification schema indicated earlier, it may occur that the links in our case study could for example be assigned as shown in Figure 105.

Figure 105 Assigning Links to Classes

<table>
<thead>
<tr>
<th>Link number</th>
<th>Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>11</td>
<td>Type 2 (divided highway)</td>
</tr>
<tr>
<td>12</td>
<td>Type 1 (simple link)</td>
</tr>
<tr>
<td>13</td>
<td>Type 2 (divided highway)</td>
</tr>
<tr>
<td>14</td>
<td>Type 1 (simple link)</td>
</tr>
<tr>
<td>15</td>
<td>Type 2 (divided highway)</td>
</tr>
<tr>
<td>16</td>
<td>Type 1 (simple link)</td>
</tr>
<tr>
<td>17</td>
<td>Type 2 (divided highway)</td>
</tr>
<tr>
<td>18</td>
<td>Type 1 (simple link)</td>
</tr>
<tr>
<td>19</td>
<td>Type 2 (divided highway)</td>
</tr>
<tr>
<td>20</td>
<td>Type 1 (simple link)</td>
</tr>
<tr>
<td>21</td>
<td>Type 2 (divided highway)</td>
</tr>
<tr>
<td>22</td>
<td>Type 1 (simple link)</td>
</tr>
</tbody>
</table>
Intersections are similarly mapped as shown in Figure 106.

**Figure 106 Assigning Intersections to Classes**

<table>
<thead>
<tr>
<th>Intersection Number</th>
<th>Intersection Assignment</th>
</tr>
</thead>
<tbody>
<tr>
<td>n1</td>
<td>Type 3 Simple cross-roads</td>
</tr>
<tr>
<td>n2</td>
<td>Type 1 Basic Node</td>
</tr>
<tr>
<td>n3</td>
<td>Type 1 Basic Node</td>
</tr>
<tr>
<td>n4</td>
<td>Type 1 Basic Node</td>
</tr>
<tr>
<td>n5</td>
<td>Type 4 Basic Rotary</td>
</tr>
<tr>
<td>n6</td>
<td>Type 5 At grade intersection (overpass)</td>
</tr>
<tr>
<td>n7</td>
<td>Type 8 Cloverleaf</td>
</tr>
<tr>
<td>n8</td>
<td>Type 8 Cloverleaf</td>
</tr>
<tr>
<td>n9</td>
<td>Type 3 Simple cross-roads</td>
</tr>
<tr>
<td>n10</td>
<td>Type 3 Simple cross-roads</td>
</tr>
<tr>
<td>n11</td>
<td>Type 1 Basic Node</td>
</tr>
<tr>
<td>n12</td>
<td>Type 1 Basic Node</td>
</tr>
</tbody>
</table>

**G5.3 Route Creation**

*Route 1*, the (red) striped line represents the “Red bus route”. It is made up of links 11, 111, 14, and 18. It traverses or touches five intersections (or nodes), which are n1, n7, n5, n6 and n4.

Through the look-up table, using the assignment of highway types, east to west, the route becomes a four-stage sequence of:

1. Divided highway
2. Divided highway
3. Simple link
4. Simple link

The five stage intersection types traversed by this route, east to west, are:

1. Simple cross-roads
2. Cloverleaf
3. Basic Rotary
4. At-grade intersection
5. Basic node

This now becomes a nine-stage combined route of:

Simple cross roads - divided highway - cloverleaf - divided highway - basic rotary - simple link - at grade intersection - simple link - basic node

The essence of the approach is that that above objects are provided encoded intelligence so that the following operations (i.e., “connections’) are known by the respective objects:
Three immediate potential key advantages of this are:

1. **Connectivity Checking:** The connections in the above cases have been exampled only for illustrative purposes and in reality may not be likely in all real-world situations. For example, in the first case above, the simple cross-roads would not in-reality connect to a divided highway (there would be a more complex type of intersection). Typically, DOTS will have many coding errors in their datasets and by *type coding checks*, errors in the network setup may be more readily detected. The potential benefit is automation of network data integrity checking and in data cleanup.

2. **Traversal Path:** The route that is created across the above objects can trace out a potentially more accurate “automated” path (accurate in at least in “planning level” terms) than is typically currently the case. For example, by coding an intersection as a “rotary” rather than a simple node, the rotary maybe given basic parameters, such as center and radius that will facilitate:
   
   a. Knowledge that in the US, the vehicle will pass to the right of the center of the rotary
   b. An approximate estimate of the traversal path on the rotary.
   c. Knowledge of other information that may be use, for example how the rotary likley connects to certain highway types.

Of course, none of these estimates will be as accurate as detailed engineering calculations. However, they may be a sufficient addition to accuracy to be worthwhile for DOT’s to gain a significant operational benefit. In fact, such forms may best match many operational transportation community user requirements for “sufficient”, but not application superfluous information to meet their particular operational tasks. For example, for many “planning-level” highway data management and analysis purposes, for example a cul-de-sac might be adequately described (or a suitable representational form generated) through just 2 measurements (that is, a length measurement, and the radius of the proscribed turning circle). This would potentially be in comparison to potentially processing hundreds if not thousands of survey points from a more detailed engineering model of the facility. The engineering data is wholly appropriate if a redesign of the cul-de-sac was for example being contemplated. However, it might not be necessary to process this amount of data to gain reasonable display of the cul-de-sac for many operational application purposes, or, even for example to do a preliminary calculation of the amount of salt and sand that might be needed (and snow removed) for a winter snow plough operation.

3. **Network Components.** The approach here fully expanded out allows a reasonable, but not excessive, additional level of network components to be identified and data managed. This may most importantly include components of large
intersections (such as clover-leaves, associated highway facilities such as service roads, and highway ramps).

By now most DOT’s (or their staff in the field) have put in place solutions to the what is commonly referred to as the “unploughed ramp problem”. This occurs when for example a ramp exists between two roads between different highway or maintenance jurisdictions. While field operators of for example snow plough vehicles may have enough local working field knowledge to plough the ramps, those managing databases may have “unploughed ramps”.

The explicit addition of these extra components may seem to make a relatively small difference. However, if the total sum of ramps, services roads, and the like, etc, is added it can make a relatively significant difference. For example, Nova Scotia is one of the smallest provincial/state level jurisdictions in North America. It still spends $350m a year on winter snow and ice removal operations (some of the northern US states spend more). If an “appropriately more accurate” depiction of the highway network (but, not excessively accurate, from an operational point of view), can help them allocate sand and salt piles and its delivery patterns and coverage more efficiently (even by 0.5, 1, 2 or 3% per annum), this can pay for the cost of the network data conversion and set-up exercise.

Details of the green route are provided below. For comparative purposes, Route 2, the (green) dotted line represents the “Green bus route”. It is made of links 17, 14, 112, and 110. It traverses or touches five intersections (or nodes) n3, n5, n6, n8 and n10. Through the look up table, using the assignment of highway types, south to north, the route becomes a sequence of: Divided highway, and four Simple links. The intersection types traversed by this route, south to north, are: Basic node, Basic Rotary, At-grade intersection (overpass), Cloverleaf and Simple cross-roads.

Both the red and green routes traverse link 14; a convention is needed whether data associated with this link (such as say a bus stop) is associated with one route or both.

G 6. Issues with The Framework

This section briefly reviews some of the possible issues with the framework as laid out here.

G 6.1 Potential Limitations of the Approach

A number of limitations with the approach may be suggested. These include:

1. Nesting of Data Elements: There may be issues in nesting data structures within each other. For example, a change in a lower level data element (such as, “a link) needs to propagate through to a higher order element (such as, “a SuperRoute”). While through inheritance and object properties OO approaches may facilitate the dealing with such issues, they do obviate the need to design all of the logical relationships and structures. For example, encoded logic would need to determine that if a sub-element is removed from a route, the route will no longer be continuous.
Counter Argument: While there is a cost to encoding such logic, the lack of such logic means that the user has to manually undertake and enforce such checks. This work maybe well suited for computer operation, particularly on large DOT datasets. Failure to do this, means that many datasets have basic elemental flaws in them (as it commonly found on the examination of many DOT datasets as found in Chapter 6). Many COTS and POTS have had in them for sometime at least basic network integrity maintenance checks. Faster processing power enables such checks to be performed nearer to absolute real time.

2. Performance and Storage: Typically OO approaches have been slower than other approaches (as for GIS, geo-relational). The approach laid out here may impose additional overhead and processing (time) costs.

Counter Argument: Desktop computers are increasingly powerful. Such machines increasingly have large and fast hard-disks; 1.5 Gigahertz processor machines expected this year, and perhaps 2 or 3 gigahertz machines in use before any scheme proposed here could be more fully developed and implemented. Also, OO technologies (i.e., languages and databases) have improved in operational efficiency and processing speed. These developments indicate form field experience that given the size of DOT datasets, lack of processing power should not restrict the development of the framework proposed here. (In prior years, this was formerly not the case with the application of OO approaches to spatial application processing).

3. Standard Object Library: The framework requires a common adoption of standard network object library. As reviewed in a little detail in Chapter 9, on institutional issues, national public agencies have been reluctant to enter the standards making market.

Counter Argument: Such a framework may be adopted by OGC and OMG who are aggressively adopting such frameworks in other areas (see Chapter/sections 5.9 and 5.10).

4. Legacy Conversion: The framework requires conversion of existing transportation networks and route systems into this format. This effort could be substantial.

Counter Argument: Firstly, conversion routines could be written to facilitate this effort. Secondly, this conversion could occur when a DOT or local road authority was either do a major recast of its LRS (as Iowa is currently) or is implementing a LRS for the first time (as many MPOS and local road authorities are now doing).

5. Vendor Support: It requires vendors to support it to be field-useful. This argument is of significant concern to many transportation practitioners who increasingly rely on COTS and POTS GIS software.

Counter Argument: Methods for the storing of linearly referenced data were the focus of some attention in the early 1990’s with the introduction of Dynamic Segmentation (see chapter/section 4.4). Since that time there have been some
incremental improvements in technology to undertake DS, but arguably vendors have been reluctant to make significant improvements in their toolboxes until a clearly improved and exposited framework was laid out. The further development of the approach here, or alternate but similar approach, with some buy-off from the wider transportation community of its perceived benefits, would provide such necessary the backing and frame.
Appendix References


Odell, J.J. Advanced Object Oriented Analysis and design Using UML. 1988


APPENDIX H  CHAPTER SUMMARY OBSERVATIONS

CHAPTER 1:

1. **History of Use**: Linear traversal measurement is an ancient activity.
2. **Role**: Linear referencing is well established as the principle means by which transportation agencies manage network-related data. Linear referencing is now viewed as just one type of location referencing within a larger *location* referencing system. The implementation of LRS in GIS has become the normal pathway to an integrated highway location referencing system. Full integration between linear referencing control databases and GIS has become desirable as full-featured display and analysis of current and historical information moves from wishful-thinking to a practical reality.
3. **Research Basis**: Only in very recent times has it been studied more formally and in-depth. It is topic for which a prior research base has not been firmly established.
4. **Class of Problems**: The study of LRS involves consideration of the class of “messy” spatial problems.
5. **Spatial Varieties**: Transportation highway networks on which LRS are placed come in a variety of real world forms and complexities.
6. **Economic Investment**: There has been significant historical investment by transportation agencies in collecting linearly referenced data.
7. **Technology Development**: This investment continues today with the use of GPS-equipped highway data collection vans. Emerging technologies, new methods of data collection and the expanding responsibilities of transportation agencies have changed the way the linear referencing is viewed and implemented.
8. **Advantages of LRS**: While there are some disadvantages to LRS, and new technologies such as GPS make available 2D data in an increasingly cheap and accurate form, the use of LRS has intrinsic advantages. The advantages include:
   a) It is generally an intuitive system to use in the field
   b) It pre-assumes existence on the network, so there is not the problem of “snapping” to the network
   c) It allows for data to be collected where there is a change in conditions. Therefore, if the data condition does not change for 101.1 miles, there will only be a 0 mile and a 101.1 offset indicators of change to be recorded in the database.
9. **Data Models**: One of the strengths of LRS is that it readily lends itself to data models. One of the challenges of LRS is that it lends itself to data models. The number of complexities in real world networks has been noted above.
10. **LRS Development**: The design and refinement of linear referencing systems will continue with greater sophistication to meet new objectives. Greater data integration will enable more thorough analyses to improve the decision-making process of where investments are best made in the transportation network to meet various (often conflicting) needs. Linear referencing methods, as one component of robust location referencing systems, will provide an essential framework for development of integrating transportation information systems (ITIS), intelligent transportation systems (ITS), and related endeavors.

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To meet DOT stated needs, newly designed applications in LRS, GIS-T, and ITIS must be flexible enough to readily accommodate changing software and data collection techniques. Software itself is evolving towards a fully open architecture through object linking and embedding such that sub-applications are modular. Preserving the potential for future growth requires an ability to accommodate change. Arguably, this decade has marked a fundamental transition where GIS and LRS practices no longer dominate transportation data management, but have become subservient tools beneath greater visions of “ITIS”.

CHAPTER 2:

11. **Transportation Network Analysis**: This topic (in terms of traffic generation and flow algorithms) has been well-researched. This has been accompanied by the associated development of appropriate RM and techniques. Transportation network analysis, in terms of the description and analysis of transportation networks, (that is a description of the transportation infrastructure) has been less well described.

12. **Relevance**: The work in this thesis hits on a central theme identified by Schon of relative, “relevance or rigor”. (Schon, 1987).

13. **Practitioner Topic**: LRS only has use and ultimate practicality in a “real-world” user context. The research approach adopted in this thesis needed to reflect this.

14. **Research Methods**: Planning or spatial information systems appear to have not yet had more attention given to research methodologies that are best associated with their execution. The better development of LRS may depend on the fuller development of RM’s appropriate in particular to practitioner-focused Planning and Spatial Information Systems research.

15. **Yoram Reich Work**: The work of Yoram Reich would appear particularly appropriate to develop for PIS contexts.

16. **LRS Foundational Research Base**: The fact that LRS had been little formally researched before, meant that a more “foundational” research work had to be completed here. Subsequent more focused research on individual topics that are identified from this thesis could use more focused tools. However, it is suggested that the general framework briefly sketched here, may be of more general use in setting the frame of such research efforts.

17. **Iterative Waterfall Method**: This is the research approach most akin to that chosen here. It seems appropriate for PIS research.

18. **Multi-Faceted Review**: A number of different analysis viewpoints may be appropriate for a rich practitioner domain. To ensure relevance, multi-faceted topics such as LRS have research needs which need to rest on a multi-faceted, reflective, research approach (not just for example a set of four case studies alone). The four chosen here were in-depth literature review, case studies, expert panels, and a reflective practitioner exercise.

19. **Case Studies Reliance**: Reliance on case studies alone would appear too limiting for a topic such as LRS as well as other PIS topics.

20. **Research on RM**: Further work on LRS RM would mean that the limited available resources for such work is well spent.
CHAPTER 3:

21. **Role of Definition of Networks and LRS:** LRS “sits on top of” networks. A precise definition of network is required to apply LRS.

22. **Highway Form Development:** Applying LRS on the Roman road system was more straightforward than on the more complex road systems that exist today.

23. **Messiness of Spatial Data:** All spatial data is inherently messy. This includes spatial networks.

24. **Domain Language Issues:** There is a domain classification problem with networks and network features. Classification in any domain depends on training and the formal domain one represents or reflects.

25. **LRS Ontology:** Terms used with network analysis mean different things to different practitioners (i.e., they are polysemous). The creation of a standard dictionary (and an ontology of objects) which is accepted by the wide transportation community appears to be key.

26. **Data Management View of LRS:** Transportation planning and much DOT transportation data management typically look at data in a more aggregate way than for example a Civil Engineering level of analysis level. This level of detail may be appropriate for many of the management applications briefly touched on in this chapter.

27. **Model Context:** In creating application models and data models one needs to be very aware of the context and limitations of those models.

28. **LRS Model Class:** LRS is a form of spatial data model.

29. **OO Methods:** OO approaches appear to have strong relevance to LRS.

30. **Further Research:** Further multi-modal and cross transportation information community research is required on a detailed ontology for LRS and networks.

CHAPTER 4:

31. **Ontology:** It is possible to define a reasonably consistent nomenclature and set of concepts for LRS. About a dozen key terms define a significant part of the LRS field (for example: linear referencing system, linear referencing method, reference posts, mileposts, traversal reference point, offset, anchor section, anchor point, engineering stationing, control sections, event tables, and straight line diagram).

32. **LRS Implementation:** LRS has been implemented through two principal methods. These are, 1) sign oriented methods (such as mileposts and reference posts), and, 2) document oriented methods (such as SLD).

33. **Control Sections:** These establish a middle ground between route-milepoint and link-node schemes. Control sections break routes into manageable data management lengths. These may correspond to some artifact of the original construction.

34. **Event Tables:** These contain the attribute data for linear objects being modeled. Typically they have been stored in a relational database table.

35. **Flatland Distance:** Consideration of the 3-D effects of roadways can affect length measurements. These affects are not as big as sometimes otherwise postulated as, a) many of the state-maintained roads (and hence with LRS) in many states are relatively flat and the distance correction is quite small (<5%), of
the order of other sources of measurement error, and b) current DMI instruments incorporate 3D effects into their length measurements.

36. GIS: The growth of GIS has greatly facilitated the ease with which LRS may be performed with the use of COTS technology.

37. Dynamic Segmentation: This is the single most significant addition to GIS for transportation. The technology is however essentially currently in “Phase I”. The use of DS allows significant benefits in normalizing (reducing) the volume of event data held and in facilitating various types of “network overlay” operation. In fact, because GIS’s cannot do network overlay directly (only polygon overlay), DS is a necessity for network based data storage and analysis.

38. GPS: Is becoming increasingly available and cheap to use. While the physical use of the technology is well understood, the institutional use of GPS as an art and a science has yet to be well-proscribed. (This is the “data reconciliation problem”, otherwise called “the bridge over the river problem” – that is, the need to maintain a synchronicity between the accuracy of different datasets being maintained and integrated).

39. GPS v LRS: Rather than just being seen as an alternative to LRS, GPS in the field in fact has practically promoted the use of GPS, through the use of automated data collection vans which collect various types of highway data along linear traversals. The LRS definition of data may contain just the right amount of information for many classes of highway analysis (e.g., pavement, safety, congestion, etc.).

40. Further Work: This would consider as a minimum:

1. Producing an even tighter lexicon of LRS with clear examples
2. Providing agency-level institutional guidance on the set-up use of GPS (in particular as it related to LRS)

CHAPTER 5:

41. No winner: No one general model has gained more universal popularity and acceptance across DOTs, vendors, and government organizations.

42. Organization Preferences: DOTs seem to favor the Vonderohe approach, local agencies were important in creating the BTS standard, the federal government has supported SDTS and the ITS community the ITS Datum. GDF is popular with data vendors.

43. Low Current Development Level: While there was a spate of activity on road data models in the mid-1990’s, the current position with several of the models or formats is unclear. At least some efforts deem to have at least relatively faltered.

44. GDF Role: While popular in the US with data vendors, GDF has gained popularity in Europe (where it originates). While a likely standard in the US, it is probably fair (i.e., realistic) to say its full appropriateness in a US and North American setting has not yet been made fully documented or made fully clear.

45. SDTS-GDF: There have been a number of efforts to investigate the integration of SDTS and GDF, but, in short, these seem not to have been actively pushed recently.
46. **NHCRP 20-27(2) Model:**

47. **No One model Fits All:** The above may simply reflect that no one model truly equally suits all transportation purposes. There are likely to be constraints in the use of all of the models/formats for some purposes.

48. **Documentation:** The GDF, SDTS and BTS model/formats are well documented, the others less well. All have lacked from the availability of a manual that provides wider field guidance to using and setting up road data models and LRS. The NHCRP model in particular does not provide any detailed advice on dealing with LRS field issues or how in particular in any depth how to apply the model itself in the field.

49. **Further Research:** This is required in the overlap and integration of these models.

50. **Further Progress.** It seems that further progress will not be likely on the integration of the models without some top-down national governmental push.

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**CHAPTER 6:**

Table 33 below gives a brief summary of ten of the main findings recorded in this chapter. The two immediately following tables provide some further break out detail.

Different traversal types are summarized in Table 34. It can be seen that the common recommendation throughout is that these different traversal types need to be allowed for. These reflects a practitioner goal of reasonably allowing model forms that meet clear working practices.
<table>
<thead>
<tr>
<th>#</th>
<th>LRS Issues</th>
<th>Key Observations and Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Coding traversal identifiers</td>
<td>Any method can work</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Road names a reasonable choice</td>
</tr>
<tr>
<td></td>
<td></td>
<td>More research needed</td>
</tr>
<tr>
<td>2</td>
<td>Use of separate traversals for each travel direction</td>
<td>Field use benefit from dual direction</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Logic and database issues with using</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Single traversal at the current time as issues with the current technology</td>
</tr>
<tr>
<td>3</td>
<td>Special cases for defining traversals. These include: a) divided highways,</td>
<td>SEE Table 34</td>
</tr>
<tr>
<td></td>
<td>b) ramps, and, c) overlapping traversals, etc.</td>
<td></td>
</tr>
<tr>
<td>4</td>
<td>Use of mileage equations</td>
<td>Served an important purpose in the past</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Several DOT’s use today</td>
</tr>
<tr>
<td></td>
<td></td>
<td>With new technology, now recommended that do not use</td>
</tr>
<tr>
<td>5</td>
<td>Location accuracy</td>
<td>Spatial data of varying quality</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Need to set up LRS with flexibility to deal with datasets of different accuracy and accuracy measures</td>
</tr>
<tr>
<td></td>
<td></td>
<td>More research needed</td>
</tr>
<tr>
<td>6</td>
<td>Linear referencing for local roads</td>
<td>Growing need to include local roads data as local agencies manage roads more</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Local roads more detail</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Need to include greater range of traversal types</td>
</tr>
<tr>
<td>7</td>
<td>Determining location and distance: field and office practices</td>
<td>SEE Table 35</td>
</tr>
<tr>
<td>8</td>
<td>Linear LRS maintenance and quality control</td>
<td>Need to define best working practices – work here a small start, but more needed:</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Design of LRS needs to include: a) Quality Control, b) Temporal factors, and, c) Metadata</td>
</tr>
<tr>
<td>9</td>
<td>Multimodal Integration</td>
<td>Multimodal real need if use of LRS to be extended</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Additional need to include flexibility in modeling different network forms and hierarchies</td>
</tr>
<tr>
<td>10</td>
<td>Temporal issues.</td>
<td></td>
</tr>
</tbody>
</table>
### Table 67 Traversal LRS Recommendations

<table>
<thead>
<tr>
<th>#</th>
<th>Traversal Special Cases</th>
<th>Recommendation</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Divided highways</td>
<td>Allow for</td>
</tr>
<tr>
<td>2</td>
<td>Ramps and approaches</td>
<td>Allow for</td>
</tr>
<tr>
<td></td>
<td>Provide one consistent method</td>
<td></td>
</tr>
<tr>
<td>3</td>
<td>Non-contiguous traversals</td>
<td>Allow for</td>
</tr>
<tr>
<td>4</td>
<td>Overlapping traversals, etc.</td>
<td>Allow for</td>
</tr>
<tr>
<td>5</td>
<td>One-way pairs</td>
<td>Allow for</td>
</tr>
<tr>
<td>6</td>
<td>Layered or tiered roadways</td>
<td>Allow for</td>
</tr>
<tr>
<td></td>
<td>(in states where common)</td>
<td></td>
</tr>
<tr>
<td>7</td>
<td>Service roads</td>
<td>Allow for</td>
</tr>
<tr>
<td>8</td>
<td>Individual lanes (inc. HOV lanes)</td>
<td>Allow for</td>
</tr>
<tr>
<td>9</td>
<td>Associated facilities (e.g., truck runoffs, etc)</td>
<td>Allow for</td>
</tr>
<tr>
<td>10</td>
<td>Rotaries</td>
<td>Allow for</td>
</tr>
<tr>
<td>11</td>
<td>Cul-de-sacs</td>
<td>Allow for</td>
</tr>
<tr>
<td>12</td>
<td>Proposed roadways</td>
<td>Allow For</td>
</tr>
</tbody>
</table>

The limited set of reviewed other LRS field issues reviewed are summarized in Table 35.

### Table 68 LRS Field Practices Recommendations

<table>
<thead>
<tr>
<th>#</th>
<th>Field Practices</th>
<th>Recommendations</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Mileposts and Reference Posts</td>
<td>Useful in short-term</td>
</tr>
<tr>
<td></td>
<td></td>
<td>In longer-term, GPS negate need for?</td>
</tr>
<tr>
<td>2</td>
<td>Determination of Traversal/Section Lengths</td>
<td>Be able to maintain and use different traversal measuring lengths and map these to an official log distance. Be able to use insert positional data when this is available.</td>
</tr>
<tr>
<td>3</td>
<td>Event Locations</td>
<td>Also, allow for event data with different degrees of accuracy</td>
</tr>
</tbody>
</table>

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CHAPTER 7:

61. **COTS Time Extension:** The work of Candy earlier referred to (Candy, 1995) indicates that it is indeed practically possible to make extension to existing GIS COTS software to provide time functionality. (An indication is given Table 37 of the estimated level of effort to adapt and extend existing COTS GIS software, from the possible perspective of a GIS vendor.

62. **Fundamental Changes to Core Data Model:** It may be however that the fuller and generic handling of time could in optimal form require a very fundamental change in the core data structures and approaches of GIS COTS vendors.

63. **Industry Standards:** Current industry supported initiatives through OGC (earlier referred to in Chapter/section 5.10), may help address part of these issues by providing common agreed requirements and standards for interoperability.

64. **Vendor Investment:** Given such enhancements as described here seems to be the "next frontier" of GIS adaptation and extension, it seems unfortunate that vendors have seemed reluctant to make this investment to date.

65. **Transportation Community:** The transportation community may wish to ride on the coat-tails of the wider GIS community in adopting temporal operators, as the construction of such operators will in any event likely be across industry generic implementation. The problem with this approach is that no one industry has seen an absolutely critical need for time measures, and vendors have not felt it worthwhile to make their own investment.

66. **Current DOT Practice:** As reviewed in this chapter, currently DOTs have employed workable ad hoc measures to undertake temporal analyses. While these measure are hardly ideal, while the agencies are struggling to complete putting in place their core data sets, concern with temporal analyses have ultimately taken “a second seat”.

67. **Future DOT Situation:** This situation is likely to change as transportation agencies complete their core GIS development and wish to undertake more detailed analyses, including temporal, of their freshly acquired and legacy datasets.

68. **Time Functionality:** The work carried out in this chapter has indicated a set of functionality that is required with LRS activities. This includes support of, a) time stamping of objects, b) time traversal points, c) multiple time measuring methods, d) time entities, e) temporal entities (such as begin and end time), and, f) track in time.

69. **More Detailed Time Functionality:** More detailed spatial time functions would include the provision to be able to answer user queries on time slices, time period analyses, “condition at time x”, time enabling of a wider set of spatial operators, time series aggregation, populating databases based on temporal measures, timepoint analysis, time-based location estimations, time metric conversions, time estimations, time/space conversions and tools for time proximity analyses.

70. **Further Research:** Further research might focus not only on the time functionality required and the exact user preferences for this from a transportation/LRS perspective. While it is true that the longer-term provision of time-based COTS tools will benefit from a precise a description as possible of exact user needs requirements of the individual domains.
CHAPTER 8:

71. **Purpose of Road Data Models:** The road models seemed to take a different cut on two basic things:
   a. **Domain:** What exactly is the transportation domain?
   b. **Components:** How do, “how do we chunk up” the national infrastructure of roads?

72. **View on OO:** OO is “more than just another data format”. It requires in short a change in thinking. Many practitioners who have started using OO techniques have said that it has taken a full year to make this change. Many objects, including objects in the transportation domain, have complex behaviors. It is necessary to understand the behavior of objects properly before one can model them.

73. **Nature of Transportation Objects:** A transportation object can be both real (e.g., roadway, bridge) and virtual (e.g., node, link and path).

74. **Multiple Geometries:** With OO, feature objects can more readily have multiple geometries. In GIS until today, features have typically had one set of geometries associated with them.

75. **Advantages of OO:** OO provides opportunities for, a) improved data modeling and simulation of real-world spatial phenomena with complex interdependencies, and, b) data generalization.

76. **Diagramming Methods:** The lack of a common diagramming method to date had been a limitation. UML offers a way forward past this particular problem.

77. **Commercial Foci:** OMG and OGC were focusing on particular sub-areas of the transportation field that their primary sponsors had identified.

78. **Training and Education:** It is possible to build something poorly in any paradigm, including OO. However, the best results in any paradigm come with training and education.

79. **Standard Transportation Features:** Much still had to be done in transportation to develop transportation object oriented data structures.

80. **Future research - Start with the Network:** Thinking about OO approaches to LRS could be facilitated by first thinking on OO data structures for transportation networks.

CHAPTER 9:

81. **Need for Toolkit Approaches:** No one LRS technical or institutional solution is likely to fit all circumstances. Approaches will need adaptation to local circumstances.

82. **LRS and GIS Efforts:** LRS efforts should be closely institutionally associated with GIS efforts of which they are technically intrinsically part. There may be occasions where for particular or special reasons where this may not be so, and then LRS should be pursued “independently but communicating”.

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83. **Top Institutional Concerns:** It was been found with GIS that, a) top management support, and b) location of the responsibility in the agency are key institutional concerns.

84. **Top Management Support:** Top management support and understanding for LRS efforts needs to be gained. It may be a fairly dry topic for many DOT top management, who may be pressed by daily operational decisions. However, the absolutely key role LRS can play in integrating and providing access to the agency’s significant legacy and ongoing data investment needs to be made clear.

85. **Organizational Location:** The four case studies reviewed in this document indicate there are a variety of organizational locations that can work but careful consideration needs to be given to these.

86. **Institutional-Technical Development Frameworks:** The literature indicates that enterprise technology frameworks that include institutional and organizational issues are likely to be more successful than frameworks that are only focused on technical aspects.

87. **Zachman Framework:** This framework is one example of an IT framework that be useful for an enterprise support information system such as LRS. A case study use of the Zachman framework with LRS needs to be made.

88. **Funding:** While not focused on explicitly in this chapter, adequate funding of the enterprise-level LRS initiative is key.

89. **National level Role:** There is currently an institutional schism between the alternative road data approaches at the national level. It would seem that despite some preliminary efforts (such as carried out in connection with thesis) to reconcile these disparate road data efforts, these are kept apart by institutionally set and distinct institutional forces. The road data model efforts as things currently stand are therefore likely not to be further integrated. This higher-level institutional issue leaves a particular issue for local transportation agencies who are likely to be faced with competing and alternative road data model and LRS demands.

90. **Further Research:** This could further identify and focus on successful LRS implementation from an institutional perspective. The nature, form and remedies for institutional issues likely to associated with LRS implementation and support would be more closely traced out. This would include gaining adequate institutional support and necessary agency actions for training and education.
End: