

The Application of Information Technologies to Public Transportation

by

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B.ASc., Department of Civil Engineering, University of
Toronto (1992)

Submitted to the Department of Civil and Environmental
Engineering in partial fulfillment of the requirements for
the degree of

Master of Science in Transportation

at the

MASSACHUSETTS INSTITUTE OF TECHNOLOGY

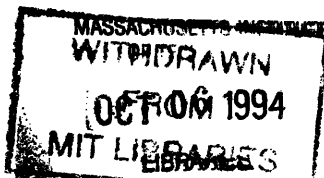
June 1994

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Abstract

This thesis investigates the potential uses of information technologies for transit applications; specifically to the real-time functions of operations monitoring and control and passenger information. To an agency that is currently considering technology to improve performance, this thesis guides the agency through the many issues that should be addressed.

The research first investigated the information needs of these two functions, the relative value of these types of information and the potential for information technologies to meet these information needs. It was found that for both functions, vehicle location information is essential, and other types of information such as passenger loads, service disruption information and vehicle status might also be useful. Information technologies have the potential to gather and deliver this information quickly and on a system-wide basis.

The thesis then investigated the wide range of technologies currently available and identified Automatic Vehicle Location (AVL) systems as the ones which best satisfies these functions' needs. AVL systems consists of vehicle location, communications, hardware and software, and human systems, and there are many issues that need to be resolved when choosing AVL system technology.

Case studies of three agencies currently implementing information technologies revealed several benefits of AVL systems. For AVL systems that have operations monitoring and control functionalities, the real-time benefits included better schedule adherence, increased safety and security, the potential for increased supervisory efficiency and the potential for improved work environments. The real-time benefits of passenger information systems included limited travel and wait time savings, improved passenger perceptions and a willingness on the passenger's part to pay a premium for passenger information. The costs for AVL systems can be categorized into development costs, capital costs and ongoing operating costs. Before these systems are implemented, however, agencies have to identify the best use for information technologies and this thesis developed a framework that can help structure the agency's selection of an appropriate information technology.

Thesis Supervisor: Nigel H. M. Wilson

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Acknowledgements

There are many people who I would like to acknowledge for their help, support and encouragement during my memorable stay at M.I.T.

First and foremost, I would like to thank my thesis supervisor Nigel Wilson, who is both a scholar and a gentleman. Not only did he help financially, providing much needed funding support through research and teaching assistantships, he was also the “compass” that put me back in the right direction whenever I would wander off.

I would also like to thank the many people who took time out of their busy schedules to assist in my research. Special mentions go out to Joel Koffman and Peter Van der Kloot at OC Transpo, Rein Alasi, Ted Harris, Dave Taylor and Eugene Catney at the TTC and all of the inspectors, controllers and system support personnel at both agencies. Both agencies run top-notch operations, and with people like these, I can see why.

There are many friends and colleagues here at MIT who have provided many special memories and enjoyable moments of friendship. Many thanks to Dawn, C.J. Geoff, Mimi, Tilly, Prodyutt and many of my colleagues in the department. Special thanks go to my mother and father in Toronto. All I do here and in the future, I do for you.

Lastly, I would like to acknowledge Eric Miller from the University of Toronto, who initially peaked my interest in Transportation studies and made my sojourn here a possibility. It has been quite an experience.

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Chapter 1

Introduction

The improvement of system performance is prime goal that every transit operator strives to achieve either by improving quality of service without substantially increasing costs, or by reducing costs without substantially degrading service. With continuing improvements in the cost/performance of computer and communications technologies, many agencies are looking to these technologies to help them optimize system performance. A subset of these emerging technologies is being used for three particular functions: operations monitoring and control, passenger information, and functions related to service planning.

The objective of this thesis is to take a closer look at the three critical service-related functions (with primary attention focused on the real-time functions of operations monitoring and control and passenger information), and the alternative technologies that can be used to improve their performance. This thesis also develops an approach for selecting an appropriate information technology and assesses the benefits of these systems to these real-time functions. Specifically, this thesis intends to answer the following questions:

- What are the needs of these service-related real-time functions and how might computer and communications systems improve system efficiency and effectiveness?
- What type of computer and communications technologies are available to be applied to these real-time functions and how can they be used?
- What are the best uses for information technology and how effective are these technologies in improving these functions?

With the information provided in this thesis, agencies interested in acquiring new systems for the purposes of operations monitoring and control, passenger information, or other functions to improve system performance will have a better understanding of the implications of their choice on overall performance. They will thus be in a better position to choose a technology appropriate to their needs and then apply the technology effectively.

1.1 System Performance

Every transit operator must be concerned about system performance. Passengers who use the system have high expectations about service quality, desiring service to be frequent, regular and structured to take them places they wish to go.

Agencies respond to the service challenge by first developing a comprehensive service plan in which the routes and levels of service are determined by considering passenger needs and trading them off against the cost of service provision. To develop an effective service plan, data needs to be collected on travel patterns and system usage. This data collection function and associated service planning functions, which primarily operate in an off-line manner, are described later in this section.

After service plans are developed, agencies must make sure that operations occur consistently and reliably on a day-to-day basis according to the plan. Any functions that support operations must occur on a real-time basis. Two of the major functions used to aid in service operations are operations monitoring and control and passenger information, both of which are described below.

1.1.1 Operations Monitoring and Control

As with any service industry, transit service must be “consumed” as it is “produced”, which places great importance on the reliability and quality of service delivery and stresses real-time oversight. The operations monitoring and control (OMC) function of a transit agency serves to ensure that vehicles are closely adhering to the operating plan and to identify and ameliorate significant deviations from the plan. Operations monitoring and control is also used to detect and deal with emergencies. The monitoring element detects vehicles that are not serving their route, not on time or evenly spaced, while the control element implements strategies to re-optimize service given the current system state. While both elements are important, the ability to intervene effectively is critical to the OMC system actually improving performance - simply detecting a problem may be of little value.

Making sure that vehicles run at constant headways can be quite challenging, depending on the technology and the operating situation. If the operating conditions are generally clear of problems such as congestion or frequent vehicle breakdowns or if guideway technology gives vehicles an exclusive right of way, then it is generally easier to maintain constant headways. Under other conditions, many situations can occur which can cause irregularities in service. The type of situations that can occur largely depends upon the vehicle and its operating environment. Vehicles that operate on exclusive rights-of-way on fixed guideways (e.g. rail vehicles) can encounter somewhat different situations than vehicles that operate on a shared right-of-way in mixed traffic (e.g. buses). Example situations and their effects on service are shown in Table 1.1.

The role of operations monitoring and control is to identify and respond to these situations as they occur in order to mitigate their effects on service quality and operations costs. Several strategies have been developed in theory and some are used in the field. Theoreti-

cally, each strategy can be effective in specific circumstances, but these strategies may not be as effective in practice. One of the reasons for this is that most transit operators have had to rely on labour intensive techniques to perform operations monitoring and control, and these techniques may not collect the information needed to make effective control decisions. Current trends, however, are to rely more on computer and communications systems to help perform this function by gathering the needed information. Advanced technologies also can improve field operating conditions, for example, signal preemption systems can selectively regulate vehicle running times by adjusting the traffic lights along a vehicle's route.

Situation	Rail System Effect	Bus System Effect
Emergency occurs on vehicle	Train is forced to stay at station. All passengers on train must wait. Trailing trains may be forced to wait until situation is resolved.	All passengers on bus must wait until situation is resolved. Bunching may occur locally but since buses can overtake each other, the effect on other buses is minimal.
Emergency right-of-way closure.	Train service is cut off for a portion of a route. Closure usually affects entire route since trains have no alternative routes.	Buses are forced to go off-route, affecting running times, headways and schedules, but service on the parts of the route not closed can still be maintained, although at a degraded level.
Heavy passenger loading	Train is forced to stay at station, affecting local headways and schedules. Train bunching may occur, but dwell times are not too sensitive to passenger loads	Bus is forced to stay at stop longer than usual, affecting headways and schedule. Bus bunching may occur since dwell times are very sensitive to passenger loads.
Vehicle breaks down	Train is forced off route and passengers must unload. Until train goes off route, all trailing trains nearby must slow or stop, drastically affecting service at a local level.	All scheduled pickups for bus on remaining stops are compromised. Bus must unload passengers as they are forced to wait for the next bus.
Operator is not available to run vehicle	Replacement operator needs to be found; if one not found, then train will not run, which will leave a service gap.	Replacement operator needs to be found; if one not found, then train will not run, which will leave a service gap.

Table 1.1: Real-time Situations Affecting Service

An aim of this research is to examine the strategies available to monitor and control vehicles and the ways in which these strategies are currently being implemented. This research will then look into the effectiveness of these strategies and how computer and communications systems might be used to improve the effectiveness of control. The research will then look into how effective these advanced technologies are likely to be at

improving this function. Although signal preemption is a potentially beneficial application for information technologies, it will not be investigated in this thesis.

1.1.2 Passenger Information Systems

Passenger information has always been an important element of any transit service since people who may want to use the system need to know what services that are being offered. The requisite passenger information can be provided in many forms, typically including maps and schedules of routes, telephone systems that provide transit information, and signs and structures identifying boarding locations. This type of static information on the operating plan may also include advertisements telling passengers of changes in service or fares and policies, or even passenger points of contact such as passenger agents who answer passenger enquiries.

All of these components are used to give passengers needed information about the system so that they can make informed travel decisions. This information changes infrequently, however, and only pertains to regularly operated service. When service is disrupted, these components cannot give the passenger any information about current performance. It is possible, however, for current information to be made available in real-time to solve this problem. Systems that are capable of doing this will be called dynamic, or real-time passenger information systems (PIS). Currently, some operators attempt to provide real-time information by doing such things as sending out inspectors to particular places to tell passengers about situations, sending voice messages through speaker-phones, or displaying information visually on screens in terminals.

These strategies may not be very effective, however because these manual systems are slow and by the time the information gets through to the public, it may already be too late for passengers to act as they would have preferred. Transit operators are searching for bet-

ter ways to communicate real-time information such as service disruptions to affected passengers by making use of computer and communications systems.

This thesis will examine the role of passenger information and its effect on overall service performance. The thesis will investigate how advanced technologies can be applied to the passenger information function to improve overall efficiency and effectiveness, and the extent to which these improvements are likely to result. A comparative analysis will also be done between the passenger information and OMC functions.

Information technologies have not only affected the operations monitoring and control and passenger information functions of transit. These technologies have found their ways into almost every facet of transit operations and planning including management (automated collection and analysis of performance statistics), planning (automated route scheduling software and automatic passenger counters), finance (automated cost accounting), dispatching (automated dispatch control) and vehicle technology (automatic vehicle control, automatic vehicle maintenance) just to name a few [Davies 28]. Some of these technologies operate in real-time (e.g. dispatching and vehicle control), but most of them are used in off-line applications. Although all of these technologies are having a profound impact in the industry, this thesis's prime focus is on the technology associated with the automatic location of vehicles and the real-time uses of that information.

1.1.3 Service Planning Function

A critical function which supports the service planning process is data collection and analysis. While the type of data that is gathered varies between agencies, it typically includes passenger counts, revenue, and vehicle trip information, [40] all of which is used in evaluating and refining service and operating plans. Historically, data collection has been labour intensive and costly, often meaning that data is collected on only a very small

sample basis, resulting in a weak base for decision-making by planners. Recognizing this, agencies have begun replacing their manual data collection systems with automated or semi-automated computer and communications systems. These new technologies promise benefits and efficiencies that cannot be achieved by previous systems.

These information systems can potentially both improve the quality of the data and reduce the marginal cost of data collection, thus enabling more data to be collected on a continuing basis. This in turn would give decision makers better information on which to base their service plans. While accumulating better data does not guarantee a better service plan, it does remove a major obstacle to good planning.

This is well illustrated by the Ottawa Carleton Regional Transportation Commission (OC Transpo), which has been using an Automated Passenger Counting (APC) system for many years which has allowed them to collect detailed data on a more frequent basis than the previous manual collection system. The result has been a clearer picture of the service that OC Transpo provides and as a result, the agency has been able to tailor their services better to meet passenger needs. At the same time, the agency has been able to reduce costs, both by replacing the manual data collection system with a less expensive automated one and by identifying and correcting inefficiencies in the service plan detected from the analysis of the data collected by their APC. OC Transpo's APC systems clearly shows that the utilization of advanced technologies for data collection to support service planning can be cost-effective. OC Transpo's APC system is investigated in more detail in the case studies chapter of the thesis.

Another example of advanced technology which can support the service planning function is the electronic farebox, which can automatically count revenue and boarding passengers. Electronic fareboxes also record running totals and can count passengers by different fare categories.

1.2 Information Technologies

The transit industry's current interest in the computerization and automation of its systems has gathered significant momentum of late. In 1994 there are 28 agencies in North America using or intending to use an Automatic Vehicle Location (AVL) technology versus only 6 agencies 15 years ago [57, 34]. In many places in Europe (e.g. London, Dublin, and Germany) and Japan (e.g. Tokyo and Osaka), systems based on advanced technologies have been in place for quite some time [34]. For the most part, full scale implementation efforts in Europe and Japan has preceded similar efforts in North America.

Transit operators have been contemplating the potential benefits of computer and communication systems for many years. Example applications such as signpost-odometer systems and passenger counting systems were developed by a few transit agencies as early as the 1970's (see Table 1.2). The main obstacles to their widespread use in the past, however, were that the technologies were extremely expensive, crude and inaccurate, and did not satisfy the data needs of these agencies.

Over the last 10 to 15 years, however, computer systems have become more powerful and less expensive, and the advance of satellite, microwave and cellular technologies have made it possible to provide inexpensive and reliable communication networks. As a result, it has become much more feasible to apply these technologies cost-effectively to public transportation than it was previously, and the range of technologies have increased substantially.

For the purposes of performance monitoring, many transit operators have similar information needs: vehicle location and (perhaps) number of passengers. There is one subset of technologies that seems to address these basic information needs: Automatic Vehi-

City	Year Initiated	Intent	Status as of 1979
Chicago	1969	AVM Demo	Completed: Emergency vehicle location done
Toronto	1974	AVM Demo	Pilot/Evaluation
Cincinnati	1975	TIS Demo	Active/Expanding
Mississauga	1977	AVL & Info System	Active/Expanding
New York City	1979	Full AVM	Being Developed
Los Angeles	1979	AVM Demo	Being Developed
AVL = Automatic Vehicle Location, AVM = Automatic Vehicle Monitoring, TIS = Transit Information System			

Table 1.2: Early North American Computer and Communication Systems^a

a. Source: Hamilton and Polhemus [34]

cle Location (AVL) systems and subsystems. An AVL technology is defined as one that has the capability of providing real-time vehicle location information with subsystems to process this data to provide information to the transit operator in a useful form. AVL subsystems include communications, hardware, software and user interface components.

Some AVL technologies are sometimes referred to as Automatic Vehicle Monitoring (AVM) or Automatic Vehicle Identification (AVI) technologies. AVM technologies are similar to AVL technologies but they may also include all of the subsystems necessary to provide monitoring whereas AVI technologies locate and identify vehicles on a more discrete basis than AVL technologies which provide more or less continuous information. In many cases, however, these terms are used interchangeably.

When a computer and communications system is designed for transit applications, the following issues must be considered:

Centralization versus Decentralization

A system can be designed to have most of the equipment, processing and decision-making at a central location, making the control center the “brains” of the systems and the

controlled vehicles “dumb” followers. Alternatively, equipment, processing and decision-making can be partially decentralized by putting more processing, equipment and decision-making capabilities onto the vehicles. Each approach to system design has specific advantages and disadvantages.

Hardware-Software-Labor Substitutability

How much hardware and software is needed, and how does the system interact with the users? Both hardware and software are needed to make a system work, and in some cases software can be used as a partial substitute for hardware. In some cases, both hardware and software can replace functions normally done by humans. The issue thus becomes one of substitutability between hardware, software and labor, and the roles each should have in a new system.

Cost and Accuracy

In order for AVL systems to be effective, accurate vehicle locations are essential. Locations that are estimated inaccurately can lead to errors in control decisions or in the real-time information given to passengers. Accuracy requires more investment, however, and there is a direct relationship between the two. The challenge thus becomes one of determining the accuracy that is both achievable at reasonable expense and adequate for real-time needs.

Discrete Versus Quasi-Continuous Updating

Depending upon the technology, it is possible to receive information about vehicles either on a quasi-continuous or discrete basis. Both types of systems gather information about vehicles, but discrete systems provide location information only periodically while quasi-continuous systems provide information more frequently. Continuous systems may provide more accurate and useful information, but may also be more costly.

This thesis examines a variety of computer and communication systems that are currently being used or have potential use for transit applications. When the thesis investigates the types of computer and communications technologies available, most of the focus will be on AVL systems and their subsystems since these technologies address a substantial portion of to agency's information needs. The thesis also investigates the general issues in AVL design defined above.

Appropriate uses for these technologies will be examined to see how they can be applied to improve system performance, with a particular focus on the operations monitoring and control and passenger information functions. Several agencies that are currently using AVL systems and subsystems will be investigated to see how these systems are applied in practice.

1.3 Literature Review

This is not the first investigation of the potential of applying information technologies to transit functions. Several previous articles have provided either a listing of available technologies and their traits or presented a working evaluation framework.

Morlok[45, 46] focuses on the benefits and economic feasibility of Automatic Vehicle Monitoring and Control (AVM/C) systems. The Morlok study was organized in five parts. The first part of the study classified the elements of an AVM/C system as a basic real-time system, a basic transit management information system and optional elements. The basic real-time elements include an Automatic Vehicle Location (AVL) component, a communications system permitting two-way communication between operators and dispatchers, a central computer, software to process incoming data, and an operator interface system. Dispatchers complement the system by analyzing AVL information and making control

decisions which are then relayed to the operators. The transit management information system normally consists of a computer to store and process data, links to compile data from multiple sources, and analysts to draw conclusions from the data. Optional elements such as passenger counters, vehicle maintenance systems and passenger information systems enhance the system and provide additional benefits. Although the optional elements listed by the study are not comprehensive, they illustrate the types of options that are available.

In the second part of the study, Morlok identified several general benefits of AVM/C systems, categorizing these benefits as both real-time and those due to better management of transit information. Some of the real-time benefits noted by the study were improved system performance, increased passenger satisfaction leading to increased ridership, and improved safety along the route provided by continuous monitoring and emergency alarms. Some of the benefits resulting from analysing post-processed data were the ability to resize the fleet, to determine routes and frequencies which better match demand, and (perhaps) decreasing costs. Many benefits were listed, but only a few of them were supported with solid evidence on the magnitude of their impacts. For instance, the study states that better control leads to increased rider satisfaction, leading to increased ridership, but little evidence was presented to show the extent of this impact.

In the next section, Morlok described the experiences with AVM/C system prototypes in three agencies; the SCRTD (Los Angeles), Cincinnati and the TTC (Toronto). For all three agencies, their AVM/C systems were described, the agency's experiences with these systems described, and each agency's own evaluation of system benefits and costs presented. In all these case studies, the agencies believed that their AVM/C systems had proven to be beneficial. In general, it was found that if these AVM/C technologies were implemented system-wide, they would reduce operating costs and increase benefits. Mor-

lok stressed, however, that although many of these agencies have had successful applications of these technologies, problems inevitably occur during the development phase. Morlok suggested that development and input that is principally at the local level tends to create a better system that exhibits fewer problems.

The study's evaluation of the benefits of these three agencies however, focussed principally on off-line use of the AVM/C data. Real-time benefits, although suggested in this study, were not investigated or evaluated in detail.

The next section of the study presented a framework that could be used to evaluate the cost-effectiveness of real-time AVM/C systems. A comprehensive evaluation using a multi-objective evaluation methodology considering both non-quantified and quantified impacts was proposed. The report suggested that design features of proposed systems should be catalogued and that all impacts, both quantitative and qualitative should be identified. Morlok does not provide any detail on how these impacts should be measured, however.

The study presents a framework for determining the costs of an AVM/C system using a simple 3 element cost model to determine cost changes from the base system:

$$\Delta TC = A (\Delta \text{Revenue-hours}) + B (\Delta \text{Revenue-miles}) + C (\Delta \text{Fleet-size})$$

where AVM/C systems are assumed to reduce revenue hours, revenue-miles and fleet size. The cost of implementing an AVM/C system is given by:

$$AI = (\text{Total-investment}) (\text{Cost-Recovery-Factor}) + (\text{AVM/C_Operations+Maintenance_Costs})$$

While this model is widely accepted, it is simplified and may not be precise enough to effectively calculate costs and benefits. Specifically, the total cost function only takes into account benefits derived from off-line analysis and does not take into account any real-

time benefits such as improved schedule adherence. The annual investment function classifies costs as capital or operating costs, but does not go any further with this breakdown. For these types of systems, there may be different types of capital and operating costs and a categorization of these types may produce a more accurate cost model.

A second relevant publication is a “handbook” for evaluating AVL systems [19, 20]. The first part of this handbook provides a comprehensive definition of AVL systems and lists their potential uses. A generic evaluation process is proposed which will be applied to 4 cities that are implementing AVL system operational tests: Denver, Milwaukee, Dallas and Baltimore. All of these cities are using or are planning to use similar technologies (Global Positioning Systems or GPS) to determine locations and all have similarly sized systems (about 1000 buses). The advantage of comparing similar sized cities is that it becomes easier to differentiate benefits due to the technology, and benefits due to the method of implementation. These operational tests can only help determine how well GPS technologies will work, however and will not evaluate alternative location technologies.

The study proposed several criteria for evaluation including:

- Financial impacts
- AVL Functional Characteristics
- Utility/User Acceptance
- Overall Transit System Performance: efficiency
- Overall Transit System Performance: effectiveness

The study then suggests measures appropriate for each criteria.

A third report [Davies 27] describes and qualitatively assesses a wide variety of advanced technologies for transit including AVL systems, passenger information systems and operations monitoring and control systems.

In assessing several passenger information technologies, Davies created a matrix in which each technology was assessed in terms of several benefit areas: time savings, fuel savings, environmental considerations, traffic safety, comfort and convenience, safety and security, efficiency and productivity, reliability and consistency and incentives. In one assessment example, automated telephone information systems were judged to produce time savings benefits by reducing waiting and booking times. The report conducted a similar exercise with fleet management and control systems including transit operations software and AVL systems. The assessment concluded that there are many potential benefits of information technologies to both the passenger information and operations monitoring and control functions. While this report provides a preliminary investigation of these technologies, it does not provide a detailed assessment nor does it provide a framework for assessment.

Each of these reports leads to a greater understanding of the likely benefits of information technology for these two functions but none of them justifies or estimates the size of these benefits in a comprehensive manner. In addition, each report evaluates the benefits of these technologies to these functions without looking at the information needs of each function. When an agency selects a technology, it needs to be sure that the information provided by the technology will be effective in carrying out its function. Also, all of these reports start their assessment given a particular use for information technology, but none actually goes back and looks at the best uses for these technologies. All of these issues will be addressed in this thesis.

1.4 Organization of the Thesis

The next chapter explores the real-time functions central to this thesis in operations monitoring and control and passenger information. The chapter first discusses the importance of these functions in improving performance by investigating the causes of service problems. The chapter then describes these functions, their information needs, and the ways by which advanced computer and communications systems could satisfy these information needs.

Chapter Three examines computer and communication technologies, with a focus on AVL systems. The chapter describes the alternative AVL technologies with their advantages and disadvantages.

Chapter Four examines the experiences of transit agencies that use AVL and related systems to help perform these functions. Three agencies (Toronto, Ottawa and London) are examined in detail and other agencies and systems will be referred to briefly to supplement these case studies.

Chapter Five synthesizes the knowledge gained in the previous chapters to present a framework for selecting technology application, presents and evaluates key issues that occur in general AVL system and design, and then assesses the potential benefits and costs arising from these real-time applications.

Chapter Six summarizes the results of the thesis and makes recommendations for further research.

Chapter 2

Potential for Application of Information Technologies

2.1 Introduction

There are many types of information that can be useful in operations management. Primary information needs can be summarized as vehicle locations, vehicle conditions, field conditions and passenger-related information. Vehicle location information is useful for determining how well vehicles are adhering to schedules and/or headways, and for possibly giving priority to transit vehicles at traffic signals. Vehicle condition information is useful for ensuring that vehicles are safe, operating correctly and are well utilized by passengers. Field condition information is useful to detect any circumstances along routes such as congestion, accidents or road closures that may affect service. Passenger-related information is useful to detect vehicles that have heavy loads, overloading of passengers at stations, or passengers requiring assistance. Table 2.1 summarizes these information types.

There are two possible uses for this information in real-time: relaying it to human (or automated) “decision-makers” who make real-time decisions on the operation of the system (the operations monitoring and control function), or relaying it to passengers who then use this information to help make their own travel decisions (the passenger information function). The use of this information is to help remediate problems that occur in service. This chapter focuses on the causes of unreliability that occur during service operations, the specific information needs of the two functions to help remediate these problems and the extent to which information technologies can help satisfy these information needs.

Information Type	Use of information	Examples
Vehicle location	Schedule adherence, headway adherence, signal pre-emption	Relative location, absolute location
Vehicle condition	Ensuring safety of vehicle and making sure adequate service is being provided	Oil pressure sensors, tire pressure sensors, passenger loads, emergency alarms
Field condition	Detection of abnormal conditions along routes	Accident locations, road closures, emergency situations
Passenger related	Ensuring safety and service to passengers	Passenger load on vehicles, passengers at stops, passengers in need of assistance

Table 2.1: Information in Transit Operations Management

2.2 Causes of Unreliability

In an idealized environment, all trips that were supposed to be run would be run on schedule, 100% schedule adherence would occur, and there would be no accidents or disruptions that would compromise the reliability of service. In reality, most operating environments are far from ideal. There are many events that can occur to disrupt service, and knowledge of these causes is an important first step towards dealing with the problem.

In August, 1982, a Transit Reliability Workshop[1] was held with experts from various disciplines discussing transit reliability. Although all aspects of reliability were discussed, the participants' comments on unreliability caused by route conditions are of most relevance here. The workshop came up with many route-related causes of unreliability and categorized them into four different types: planning and priority/controllable, real-time/controllable, planning and priority/exogenous and real-time exogenous. One reason behind this classification was that more effective planning could be used to remedy causes which are systematic and predictable, while for unpredictable causes, real-time interven-

tion may be needed. Some of these causes can be controlled or mitigated by the transit agency while others are exogenous and largely beyond the agency's control. Table 2.2 summarizes some of the different causes of unreliability that were identified in the workshop.

	Planning	Real-Time
Controllable	Route and network design schedule planning Variation in demand and running time, seasonal Stop frequency and location Operator behavior -- predictable aspects Route length Vehicle design -- loading/unloading characteristics High service frequency Overloaded buses Predictable boarding and alighting Form of fare payment	Vehicle breakdowns Poor dispatchings from terminal Late pullouts from garage absenteeism -- unpredictable
Exogenous	General traffic conditions which are predictable Demand variation -- predictable Climate Other street conditions (e.g., construction)	Unanticipated traffic disruptions Weather Fires and accidents Unpredictable events (e.g., length of baseball game) Unexpected large demand variation

Table 2.2: Route-Related Factors Influencing Reliability

This table suggests that many of the causes of unreliability are systematic and can be accounted for and controlled with good planning. Chapter 1 has already shown how advanced technologies such as OC Transpo's APC system can gather the information needed for good planning to deal with some sources of unreliability. What is of primary interest here are the causes that require real-time detection and subsequent action.

What can be immediately observed from the list of real-time sources of unreliability is that many of the impacts can be mitigated if the time and location of the triggering event are known quickly. For instance, when a vehicle breaks down, if the time and location of the breakdown is known, repair crews or an extra vehicle can be sent out to remedy the problem. Also, if an operator drives constantly behind or ahead of schedule, the more

quickly this behavior is detected, the more quickly it can be remedied. Alternatively, information can be relayed directly to passengers who, when notified of the problem, might change their travel decisions to benefit them. Generally, the more quickly the incident is detected and responded to, the less the negative impact to both the service and passenger effect.

2.3 Operations Monitoring and Control

One function that responds to problems of unreliability is operations monitoring and control. The function's first requirement is to detect any situation possibly requiring intervention, which requires extensive information about the general conditions of the transit network. In the past, much of this information was gathered and relayed manually to decision-makers, but information technologies have the potential to gather more information and then to relay this information faster.

When supervisors detect a particular disruption on the transit network, they need to select a control strategy, based on gathered information, that is likely to remedy the problem quickly. Traditionally, this has been a completely manual process, relying heavily on the experience of the decision-makers. While this can be effective, the approach suffers from typical limitations of human systems such as slow detection times, slow response times, inadequate information for decision-making and inconsistent decisions. Information technologies have the potential to assist in the decision-making process both in the data gathering process and in suggesting control procedures or in the extreme, automatically enacting control procedures. Some of these control strategies are described next.

2.3.1 Control Strategies

The Transit Reliability Workshop proposed various approaches to improving reliability, many predicated on better planning, but some based on real-time intervention. In particular, holding strategies (where individual vehicles are delayed at points along their route if they are ahead of schedule in order to maintain schedules) were viewed as having considerable potential to improve reliability. For this strategy to be most successful, however, information on vehicle locations is needed.

To deal with exogenous real-time events such as road emergencies or road closures, the participants felt that there needed to be good communications between the operators and the control supervisors. Many times this would mean a high quality radio network system that allows operators to notify supervisors on the occurrence of exogenous events so that supervisors can quickly assess the situation and make remedial changes.

Levinson [40] also identified several strategies that could be used to restore operations to schedule (see Table 2.4) and the Chicago Transit Authority (CTA) has identified many current and potential strategies for improving bus operations reliability (see Table 2.5).

One of the more complete efforts that links the evaluation of control strategies with information needs and the uses of improved technologies is contained in a series of Master's theses conducted at the Massachusetts Institute of Technology. Fellows [32], Deckoff [29], Macchi [41] and Soeldner [61] all evaluated different control options for the Boston MBTA Green Line (a light rail line with multiple branches) and the potential for the newly installed Automatic Vehicle Identification (AVI) system had to improve performance. Fellows's [32] work provides the most useful information for this thesis and, for this reason, is the principal thesis to be cited.

Problem	Strategy	Method
Service Disruption (Accidents, vehicle breakdowns, emergencies, weather)	Service Restoration	Replace defective bus Divert bus from another route Provide standby or gap bus Use supervisors' vans Reroute bus Run shuttle bus Turn back (shortline) bus Let following bus pass leader Provide relief operator Introduce bus delay
Late or Early Bus	Schedule Control	Hold early bus Change bus speed (slow early bus, speed late bus) Reduce layover time
Heavily Traveled Bus Routes - Delays or Overcrowding	Headway Control	Maintain headways (schedule adherence not required) Let express buses run "free" on outbound trip from CBD
Delays and Overload at Major Boarding Points	Load Control	Provide empty buses at terminal or major generator Provide starter at terminal Change fare collection practices
Absenteeism or No Show	Extraboard Management	Require operators to make extra trips Hire overtime operators Modify extraboard procedures

Table 2.3: Bus Control Strategies

Fellows, citing previous research, listed the different control options available or proposed for the Green Line and the information needs of each. A description of these control strategies and the information needs specific to the Green Line are summarized below:

Short Turning

In a short turn maneuver, a train is turned back in the opposite direction before it reaches its scheduled terminus in order to even out the effective spacing between them if bunching is occurring. In addition to evening out headways, short turning can also be used to move a train closer to schedule if it is presently behind schedule. This is done at the cost of forcing passengers destined to downstream points off the train to wait for the next one.

On fixed rail lines, short turning can only be conducted at points where the track structure allows this.

Service Restoration Actions	Domain	Current Status at CTA
Preempt traffic signals	Single bus	Not in use - no traffic signal preemption capability
Limited stops with passengers	Single bus	Not current in use, but formerly an operating strategy on "boulevard" routes
Express down a different street	Single bus	Currently in use, using expressways and Lake Shore Drive
Drop off passengers only	Single bus	Current used rarely, if at all
Express to a later point in trip	Single bus	Not currently in use
Turn before terminal	Single bus	Currently in use
Pick up run beyond start point	Single bus	Currently in use for late garage pull-outs
Operator continues past relief point	Single bus	Currently in use when one operator fails to relieve another
Hold back leader	Single bus	Currently in use
Relief operator relieves other than scheduled operator	Single route	Currently in use
Operator exchange	Single route	Currently in use
Follower picks up passengers	Single route	Currently in use whenever a service problem results in passengers being dis-commoded
Spread the terminal	Single route	Currently in use
Spread the interval	Single route	Currently in use
Pass another bus	Single route	Currently in use
Reschedule the street	Single route	Currently in use, primarily for inclement weather conditions
Emergency reroute	Single route	Currently in use, for fires, emergency road repairs, etc.
Fill with pull-in	Single route	Currently in use
Pull-out instead of relieve	Single route	Currently in use, where the relief to be made by the operator will not be there due to a service problem
Jump buses	Single route	Currently in use in case of a defective bus at a terminal
Bus change brought out by Maintenance	Single route	Currently in use in case of a defective bus on the street

Table 2.4: Service Restoration Actions^a

a. Source: Chicago Transit Authority [18]

Analyzing a week's worth of records at one Green Line station, Deckoff [29] proposed a set of decision rules that can be used by inspectors to determine which vehicles to short turn. He identified the minimum information needs for the short turn procedure to be the preceding two headways on each branch line. Other information such as real-time passenger accumulation rates and scheduled destinations, following headways, train lengths and running times between locations would also help inspectors make the short turn decision.

Expressing and Running Light

When a train is expressed, it makes no passenger stops for a certain portion of a trip. The running light strategy is similar to the express strategy except that no passengers are on board the train while it is expressed. In both cases, trains are speeded up in order to even out headways if bunching is occurring upstream of the expressed train and/or to bring them back to schedule if they are behind. This comes at the cost of a set of passengers being forced off the train to wait for the next one, thus the best points to express trains are usually at points where both the passenger load is light and there would be benefits to many downstream passengers. Macchi [41] developed mathematical models to help determine when these strategies would be effective. He then proposed decision rules that required information needs of preceding and following branch headways, estimated time savings due to expressing, passenger loading.

Holding Trains

Sometimes it is necessary to "hold" a train at its current location for a time because it is ahead of schedule or the preceding headway is very short. This is the least disruptive control action since it does not require any passengers to be forced off the train. Fellows identified the most important information needs for this strategy to be preceding and following branch-line headways (to determine whether holding would generate more even headways) and following any-line headways (to determine the maximum holding time

without blocking a following train). Since holding could be done at many more points along the line than the other strategies (theoretically limited only to the number of inspectors collecting headway information), Fellows identified this strategy as the one that would benefit a great deal from system-wide headway and schedule information.

Adding Trains

On the Green Line, a small number of trains called “Run as Directed” (RAD) trains are kept on side tracks and used to fill in service gaps caused by incidents. This benefits passengers who arrive in the service gap who would otherwise have had to wait a long time for service. In order to know when to add a train into service, Fellows suggested that system-wide location information for all trains, the locations of RAD trains and the nature and location of the incident are needed.

Managing Service Disruptions

Many of the above control strategies only deal with minor incidents. Sometimes incidents of a more disruptive nature occur, such as a vehicle breaking down in the middle of its run, and the staff are required to detect and respond to these major service disruptions as quickly as possible. Fellows argued that a “whole-system” view, implying centralized monitoring and control would be able to detect and respond to major service disruptions faster than a system where decentralized control is in place. Fellows also suggested that the ability for control staff to focus in on specific areas of the system would improve the monitoring and control of service disruptions.

Fellows then investigated the control environment that is currently in place on the Green Line. Currently, monitoring and control is being conducted in a highly decentralized manner with inspectors, dispatchers and stationmasters all having some limited control responsibilities. Decisions on different control strategies are made by different individuals, often at different locations. For example, decisions on short turning vehicles

are made by an inspector at one station, while decisions on expressing vehicles are made by an inspector located one station inbound. The decision is often made given only information local to the decision-maker.

Sometimes, decision-makers have information about other parts of the Green Line through limited communications with operators and other inspectors but they do not always consult with other inspectors or operators before making their decisions. The dispatcher at central control can also make control decisions based upon limited information provided via telephone, radio and electronically, but the dispatcher lacks the local information available to inspectors and operators. Generally, it is the inspector, not the dispatcher who makes most control decisions as illustrated in Table 2.7.

With this control structure, some, but not all of the information needs for these strategies are being met. For the short turning, expressing and holding control options, inspectors have knowledge of preceding headways, but lack knowledge on following headways

Control Action	Decision-maker
Short-turning	The Boylston inspector (for Park Street short turn) or the Kenmore inspector (for short turn at Kenmore)
Expressing	The Park Street inspector or inspectors on the branch lines
Sending Trains light	The Boylston, Government Center or Park St. inspectors, or inspectors on the surface lines
Holding	Any inspector
Crossing Trains on Branch Lines	Surface line inspectors or the dispatcher
Putting Additional Trains into Service	Stationmasters or the dispatcher
Ordering Replacement Bus Service	Dispatchers

Table 2.5: Responsibilities for Control Decisions on the Green Line

and passenger accumulation rates. For the strategies that respond to major situations (e.g. adding trains and managing service disruptions), some level of centralization does aid the decision-maker, but the system is limited and slow, sometimes resulting in bad decisions. Advanced computer and communications systems like the Green Line AVI have the ability to provide the information needed to make these strategies successful.

For the short turn strategy, Deckoff estimated that additional information such as following headways would cause the strategy to be utilized more and with better success, resulting in more passenger-minutes saved. For the express strategy, Macchi suggested that additional information about neighboring headways and predicted time savings could greatly improve the success of this strategy. Macchi also noted that if passengers were notified of these controls sooner, their annoyance would be minimized [73]. As will be shown in Chapter 4, these types of systems have the potential to provide this type of information on a more system-wide level.

For all of the strategies listed in this section, location information is seen as crucial to support the control decision. It seems that other types of information that would be useful would be passenger-related and incident-related. The uses and value of these information types for various operations functions are described next.

2.3.2 Information Needs and Uses

When a decision-maker needs to make a decision involving intervention in operations, he or she would like to have as much relevant information as possible. In a perfect world, the decision-maker would be able to obtain all relevant information, but information can be expensive, and some information is more important than others. When an agency is deciding which types of information is most important, several issues arise. They must decide upon the type and amount of information, the level of precision, and the means by

which information is to be collected. All of these decisions will govern the cost of information collection. There is also the critical issue of what to do with the information once it is collected.

Some types of information are more useful than others. For instance, knowledge of schedule adherence may be useful for determining whether a particular type of service control is needed, but real-time information about the operational status of a vehicle (e.g. engine status, tire pressure, oil pressure) may not be as useful for routine decision-making because of the low frequency of mechanical problems during operations.

The level of precision of information is another important issue. Some information types like location, schedule adherence and headway adherence would require a greater level of precision than other information types such as passenger loads. In each case, the level of precision should be based on the cost of a given level of precision versus the risks and impacts of bad decisions. A more detailed discussion of precision issues is presented in Chapter 5.

The means of information collection may be just as important as the information being collected. Information technologies have given agencies the opportunity to gather certain types of information automatically and in the future, these technologies may also provide the option of making decisions automatically. Each agency must decide upon the approach to take in order to minimize costs and maximize effectiveness.

Table 2.6 summarizes the types of information that can be useful for operations monitoring and control, the uses of the information, the means by which this information can be gathered and the how valuable the information is in helping make good decisions. In this table, it is assumed that all information types are gathered on a system-wide level rather than local level and that the information is gathered to an acceptable level of precision.

Of all of these information types, real-time location information is by far the most important, since without it, neither monitoring nor control is possible. Thus, any operations monitoring and control system must have at its heart the ability to gather location information; all the other information types might be viewed as add-ons. The secondary information types are always used in conjunction with location information (e.g. passenger loads at a location, or on-time performance at a location, etc.).

Information Type	Use for information	Information gathered by	Value
Location	Monitoring of service quality	Automatic means	High
Headways	Headway adherence, proxy for other measures, necessary for some control measures	Software to process location data	High for making decisions on high frequency routes
On-time performance	Schedule adherence, proxy for other measures, necessary for some control measures	Software to process location data	High for making decisions on low frequency routes
Passenger load on vehicles	To evaluate possible control actions	Operator or automatically through passenger counters	Moderate
Farebox revenue	A proxy for passenger load	Hardware and software	Low
Passengers at transit stations	To evaluate possible control actions	Video cameras, turnstiles	Low
Incident detection on network	Vehicle routing	Operators, detectors, video cameras	High
Operator and vehicle status	Used to determine if operator can make run or needs assistance, also helpful if vehicle breaks down	Operator, perhaps automatic monitoring	High

Table 2.6: Types of Information for Operations Monitoring and Control

2.4 Passenger Information

Another function that responds to problems of unreliability is passenger information. Unlike private transportation services, in which the user has control over trip start times, transit passengers have no control over service in the short term. They must wait for vehi-

cles and will only be sure of the service when the vehicle arrives. Because of this, passengers are liable to get anxious and their wait times tend to be stressful because of the uncertainty of arrivals and unreliability problems can exacerbate the stress. Giving information about system status to passengers helps to alleviate this source of stress.

Some type of static passenger information is already provided by all agencies in the form of schedules and route maps. Information on schedules at stop locations gives partial reassurance that vehicles will arrive at certain times and locations, but if vehicles are off-schedule, this information loses its value. It is for this reason that some agencies are considering relaying real-time information to passengers. In this manner, if passengers are made to suffer because of off-schedule vehicles, they will at least be aware of the delay and can revise their travel plans if necessary.

One issue that needs to be resolved is at what point in the trip the information should be given. One possible point is the trip origin: at home for a home-based trip or at work for a work-based trip. At this point of the trip, the commuter has many decision choices still to make including mode of travel, departure time, route and possibly station [35]. Information at the origin can help in these choices and in estimating their arrival times. Systems that provide information at the origin are called pre-trip information systems and their primary function is to inform passengers about all available transit services including expected vehicle arrival times and changes to scheduled service.

Information can also be provided at the transit stop or station at which the trip starts. At this point, the commuter has less discretion available in terms of travel choices, but the utility of this information can still be quite high. Based upon the information, commuters can decide on alternate routes if they lead to a common destination or even to switch to a different travel mode. Even if the decision-making domain is reduced, information can still reduce anxiety and decrease the disutility normally associated with waiting. Systems

that provide information at this point in the trip are typically called en-route systems and they generally provide real-time information such as wait or travel times for services from the particular stop or station.

The third alternative point of information is in the vehicle itself. Here, the passenger has little decision-making flexibility except about possible transfers to other routes if path choices still exist. Thus, the utility of the information probably decreases since the travelers have already made most of their decisions. Systems that provide information at this point in the trip are called in-vehicle systems and they generally provide information about the current vehicle trip and (possibly) connecting trips.

In general the value of information and the decision-making flexibility of the traveler decreases as the traveler proceeds along a trip and consequently, the information needs of the passenger may also change.

Generally, the same type of information that is given to control supervisors can also be given to passengers, although in a more limited form. This section considers the information needs of passengers and the value of real-time passenger information systems to both passengers and the agencies implementing them.

2.4.1 Information Needs and Uses

The information needs and uses for passengers are a little different than the needs for operational decision-makers. Decision-makers may be able to absorb a lot of information in a less user-friendly form because of their experience and because they can be trained to become familiar with the information. Passengers, on the other hand, need to have their information presented as simply as possible. The information also differs in complexity because decision-makers need to have a wider view of the system than do the passengers, thus they necessarily need more information to make good decisions. Other than the

amount and complexity of information presentation, many of the same issues apply to passenger information; information types, use of information, value of information and means of information collection. Another important issue is the point at which the information is to be given. Table 2.8, shows the relative values of certain passenger information types.

Information Type	Use for Information	Point Where Information is Given	Information Gathered By	Value
Vehicle Location	Used in graphical displays or as a precursor for determining waiting times	Any Point	Automatic means	Very useful, but passengers need to estimate arrival times manually.
Expected Vehicle Arrival time	Providing real-time information on status of vehicles on route	At trip origin or at stop or station	Automatic means for location, automatic means for estimating arrival times	Perceived waiting times reduced, people willing to pay more for service, ridership effects not known
Passenger Loads on Vehicles	Passengers might skip vehicle if load too high	At stop or station	Inspectors at multiple points, operators or automatically	Moderate
Incident Detection	Inform passengers of delays or reroutings due to incidents	At trip origin or at stop or station	Operators, inspectors, commuters, video cameras	High if incident likely to cause a lot of delay that passenger can either avoid or know about beforehand
Transfer Route Vehicle Arrival Time, or Connection Information	Inform passengers transferring to other routes of expected arrival times of connecting vehicles	In vehicle	Best automatically, may be collected manually by inspector at transfer point	Benefits only transferring passengers and won't affect decision-making unless passenger has multiple path choices
Expected Arrival Time at End Point, or Running Times	Inform passengers of trip time in order to schedule trip and make decisions	In vehicle or at stop or station	Best automatically	May be helpful for decision-making if information is displayed at bus stop or at trip origin (e.g. home or office)

Table 2.7: Passenger Information Types

Hickman [35] suggests that estimated arrival information given at the stop is very useful to passengers and several of the London Transport studies [68, 16, 59] support this notion. Hickman also suggests that pre-trip information has the potential to be as valuable as at-stop information, but suggests further research to confirm this. Accent Research [2]

surveyed the ergonomic preferences of passenger information and found out that passengers preferred arrival time estimate information over graphical location information.

Previously, little real-time information has been given to passengers, but information technologies now allow real-time information to be provided on the route-level or even on a system-wide basis.

Chapter 3

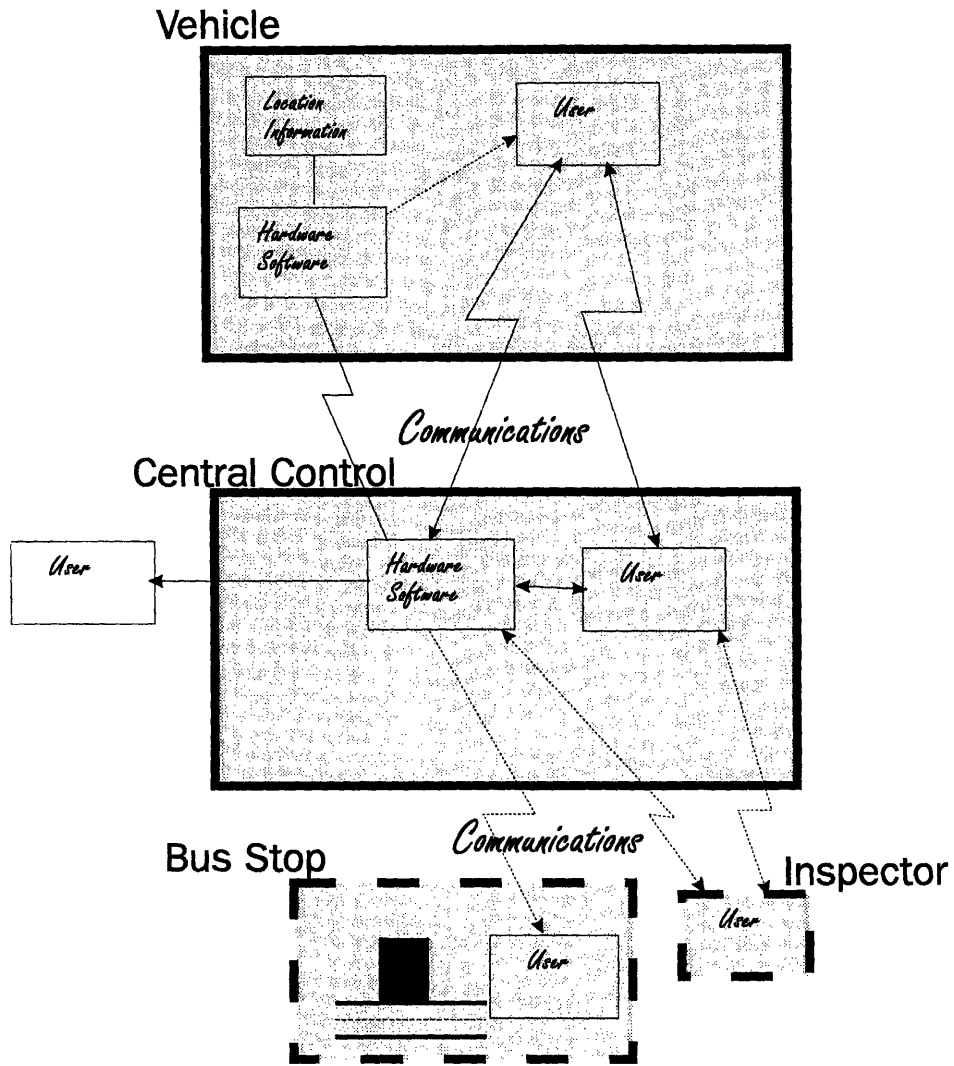
Information Technologies

3.1 Introduction

Agencies interested in implementing new technology have many choices to make on the types of systems that they want. Real-time functions such as operations monitoring and control and providing passenger information require vehicle location information and there are several alternative automatic vehicle location (AVL) technologies that are currently available. It is important to point out right away that although location is an important element in a system for operations monitoring and control or passenger information, it is by no means the only element required. Many other requirements need to be considered, such as communications, computer hardware and software, and the interactions between the people and the system. Figure 3.1 shows one possible configuration with the inter-relationships between these components.

This chapter looks at some of the principal AVL technologies and describes the ways in which they are being applied. The first section takes a brief historical look at the role of information in transit and some of the techniques that have been used traditionally in the industry as well as providing a brief literature review of articles written on this subject. It will then describe the evolution of these technologies ending with a catalog of the principal technologies available. The catalog will break down the technologies/requirements into their functional uses: location, communications, hardware and software, and human factors.

Figure 3.1: General Components of an AVL System¹



1. Dashed lines represent optional components and/or communications

3.2 History and Literature Review

3.2.1 History

Historically, many transit authorities have operated large systems with only limited information to tell them about the effectiveness of their day-to-day operations. Typically, rail system operators have had more information available to them than bus system operators because of the electrified guideways for rail systems. Information such as train locations and passage times can be relatively easily acquired from their signal and switching systems which have been in place for many years. Since rail vehicles never go “off-route” while in service, the signals, switches and circuits will always be able to keep track of train positions. Bus systems, however, have not had this luxury since they usually operate on shared rights-of-way without the guideway and signalling system to control them. Thus, it was harder to determine bus location in the past than it was for rail and for this reason, this chapter focuses on information gathering on bus systems.

The main concerns in the past that dealt with the information issue involved information about operators assigned to routes. This information was gathered to make sure that all the buses that were scheduled actually ran and departed on time. After buses went out on the streets, however, little was known about them. Information was needed for revenue and cost accounting purposes and to inform passengers about route schedules. As time progressed and both the bus and street systems became more complex, the transit agencies realized that they needed to know more about bus operations on the street. In particular, they wanted to know where their buses were, how many passengers they were carrying, and the street conditions in which their vehicles were operating. The agencies recognized that improved information could lead to improved service quality [Levinson 40].

There was a need for supervisory staff who would operate out in the field, monitoring vehicle operations and the operating environment. This staff member was commonly called the inspector, and in addition to collecting field data, the inspector was often responsible for making control decisions based upon these direct observations. Inspectors would gather information about headways and on-time performance to judge whether some form of intervention would be appropriate. This information was usually gathered at a fixed point at which the inspector was assigned.

For example, if a bus was behind or ahead of schedule, the inspector would usually tell the operator to slow down or speed up to keep the bus on time. The inspector might also tell an operator in a particular vehicle running late to short turn in order to maintain relatively even headways on the entire route. The inspector also handled emergencies such as road closures, accidents and vehicle breakdowns. It was up to the inspector to initiate the appropriate actions to alleviate the current problem.

In some agencies, the inspectors were mobile instead of being assigned to fixed locations. Given a car, these inspectors would drive over to the location of any incident, assess the situation and then take appropriate actions. Some agencies believed that mobile inspectors could respond more quickly to emergencies than stationary inspectors and could also be utilized more effectively [Levinson 40].

Street inspectors helped to improve service, but the approach still had flaws, notably that it relied heavily on local data. The inspector didn't have information on the entire system, thus he or she might make the wrong control decision. Under this approach, service control was highly decentralized, which made it somewhat ineffective since each component did not know valuable information about other components.

The next stage of information development came when the transit agencies decided to consolidate information centrally. Inspectors still worked in the field, but they also

reported their actions to, or asked for advice from, central controllers. Controllers in these locations had the potential to oversee the entire system if they were well-informed by the field personnel. They would be in communication with both the inspectors out on the street through land lines or radio and with vehicle operators via radio.

In this approach, the controllers would get a more complete view of the situation, with information flowing between the bus operators, the inspectors and the controllers. Instead of knowing information about only one point in the system, the controller would have information on many points. Technology started playing a role at this point by providing the radio communication systems or the fixed line systems.

This may have created the potential for better control decisions, but this structure also had its drawbacks. The biggest drawback was the delays encountered in sending and receiving information. With almost all the information sent by voice, communication delays could constrain the whole control process. A required series of initiations, acknowledgments and confirmations had to be completed before control measures could be implemented. By the time all this was done, the information may have already lost its value. There is usually a critical time period in which information must be acted upon before it becomes obsolete, and sometimes this limit was reached with this structure. Also, this type of approach was primarily exception-based. The operator would only initiate a conversation when he or she encountered a situation which needed a controller's or inspector's help. In all other cases, if the vehicle was not near an inspector's location, no control intervention would be made and the operator would be on his own.

One way to solve this problem would have been to increase the number of inspectors on the streets, but to be able to monitor the entire system closely, a prohibitive number of inspectors would have been required. Agencies saw a need to automate this monitoring process to break these barriers.

On the passenger information side of the service equation, the technology has advanced even less. After agencies had installed adequate static information systems, little was done to improve passenger information. On occasion, messages would be sent via speakerphones or video displays informing passengers of delays, but little else was done until automatic vehicle location became technologically feasible and less expensive. This takes us up to the industry's current stage of development.

The prime focus of the current stage is on the automatic location of vehicles and the enhanced processing of the resulting data to make it useful to the end users. These users can be operators, controllers, inspectors, managers, planners or passengers. This information can be viewed at two levels: first using the data for after-the-fact analysis and second using the data in real-time for purposes such as operations monitoring and control and passenger information. This distinction became clear in the 1970's when two Canadian transit agencies, the Toronto Transit Commission (TTC) and the Ottawa-Carleton Regional Transit Commission (OC Transpo), began thinking about ways to apply technology to improve performance.

OC Transpo focused on using technology to enhance off-line processes while the TTC focused on real-time applications. Their investigations eventually led to the in-house development of automated systems that tracked vehicle locations and processed that data into useful information. Throughout the past 20 years, their systems, techniques and objectives have changed, but their overall goals remained the same. Presently, OC Transpo has a functioning Automatic Passenger Counting (APC) system and is in the advanced stages of deploying an AVL system while the TTC has a system-wide Automatic Vehicle Location (AVL) based monitoring and control system. As these two agencies were developing their technologies to achieve their particular goals, the information revolution continued and subsequently overtook their selected technologies.

One of the main stumbling blocks that prevented many agencies from following the TTC's or OC Transpo's leads has been the risk and expense of the technologies involved. Advances, combined with decreased costs of computer and communications technology has reduced this barrier to the point where there are now over 28 transit agencies in North America who have committed themselves to this stage of development [State of the Art 57]. Many of these agencies are using or are planning to use technologies that are more advanced than the technologies used at the TTC or at OC Transpo. The TTC and OC Transpo case studies will be presented in detail in Chapter 4.

3.2.2 Literature Review

There are a few reports that describe the new technologies available to the public transportation industry and list some of the agencies that use them. There are also some articles that describes these alternative technologies. None of these articles, however, integrate the technologies and their uses.

There are a few studies that have concentrated exclusively on AVL technologies, notably Hamilton and Polhemus [34] who looked at the accuracy, reliability and cost of location technologies that are currently available to transit agencies. Included in their list of technologies are LORAN-C, GPS, GEOSTAR, OMEGA, differential odometers and flux gate magnetometers. Signposts were not included because the authors believed that they were already well understood.

The study also defined relationships between cost and accuracy and net present value and accuracy which will be presented later in this chapter. Hamilton and Polhemus concluded that an optimal system in the short term (1993 - 1995 extrapolated) would be an integrated system that included LORAN-C and dead reckoning or signpost augmentation.

One of the best sources of information that describes the types of systems that agencies are currently implementing comes from an annual report compiled by the U.S. Department of Transportation IVHS Program entitled “APTS: The State of the Art”. Initially published in 1991, updates have been released in 1992 and 1994 [21, 57 and 58]. Categorized by the use for the technology (e.g. Passenger Information, Vehicle Control, etc.), The State of the Art briefly describes the technologies that are available in each category and then describes a few transit systems that are applying them. For example, one of these categories is Automatic Vehicle Location, with one technology being signpost-odometer and one agency using signpost-odometer technology being the Toronto Transit Commission (TTC).

In each of the updates, The State of the Art identifies any new technologies that have become available since the last update, and describes any transit agencies that have recently decided to install new systems. This annual publication provides a very good overview of what is happening in the industry, but it does not go into detail. The technical aspects of the technologies are only superficially described and the updates devote at most one page to each transit agency application.

Obviously, the updates are intended to direct the reader to other sources for more detailed information which they do by listing appropriate contact names at the back of each publication. The USDOT has also released a Vendors’ Catalog [3] that lists every vendor that supplies hardware, software and consulting services to the industry. Like State of the Art, the catalog categorizes vendors by use and provides contact names, the names of clients and a short description of each vendor’s product.

In 1991, Castle Rock Consultants prepared a report for the National Cooperative Transit Research Development Program (NCTRP) entitled “Assessment of Advanced Technologies for Transit & Rideshare Applications” [28]. Like the USDOT’s “State of the Art”

reports, this report lists the new technologies that are available to transit and the transit agencies installing them. The report, however, covers more technologies than The State of the Art and includes technologies that have not yet been implemented like Automatic Vehicle Control Systems for Rideshare Applications. In addition, the report quickly assesses each technology, emphasizing breadth rather than depth.

If State of the Art is brief in describing the technologies and the agencies that use them, this report is even more brief, devoting a maximum of one paragraph to each agency or technology. This report is also a good reference guide, but like State of the Art, it does not go into sufficient detail when it comes to describing these technologies, especially for our primary focus on Automatic Vehicle Location Systems.

One report that deals specifically with AVL systems is a University of Pennsylvania study done for the Urban Mass Transportation Administration (UMTA) division of the USDOT [Morlok 45,46]. This report focuses primarily on the benefits and economic feasibility of AVL systems, but it also provides descriptions of some AVL technologies (see the discussion in Section 1.3).

Each of these reports provides important information about available technologies and their uses but they each fail to address some important topics. They do not go into enough detail in describing the technology options (AVL in particular), and they do not address the sub-systems that process this information.

3.3 Location Technologies

At the heart of any AVL system is the location technology itself. This section looks at some of the more popular location technologies and their relative advantages and disadvantages. Some of the issues related to choosing a location technology including cost,

accuracy and reliability will be discussed. Possible combinations of technologies will also be looked at. The technologies that will be investigated are Odometers, Dead Reckoning, Signposts and Passive Identification Technologies, Global Positioning Systems (GPS), LORAN-C and Map Matching. A comparative analysis will then be done across technologies, largely drawn from previous reports that have looked at this subject in detail. Figure 3.2 shows how each of these options fits into the rest of the AVL system.

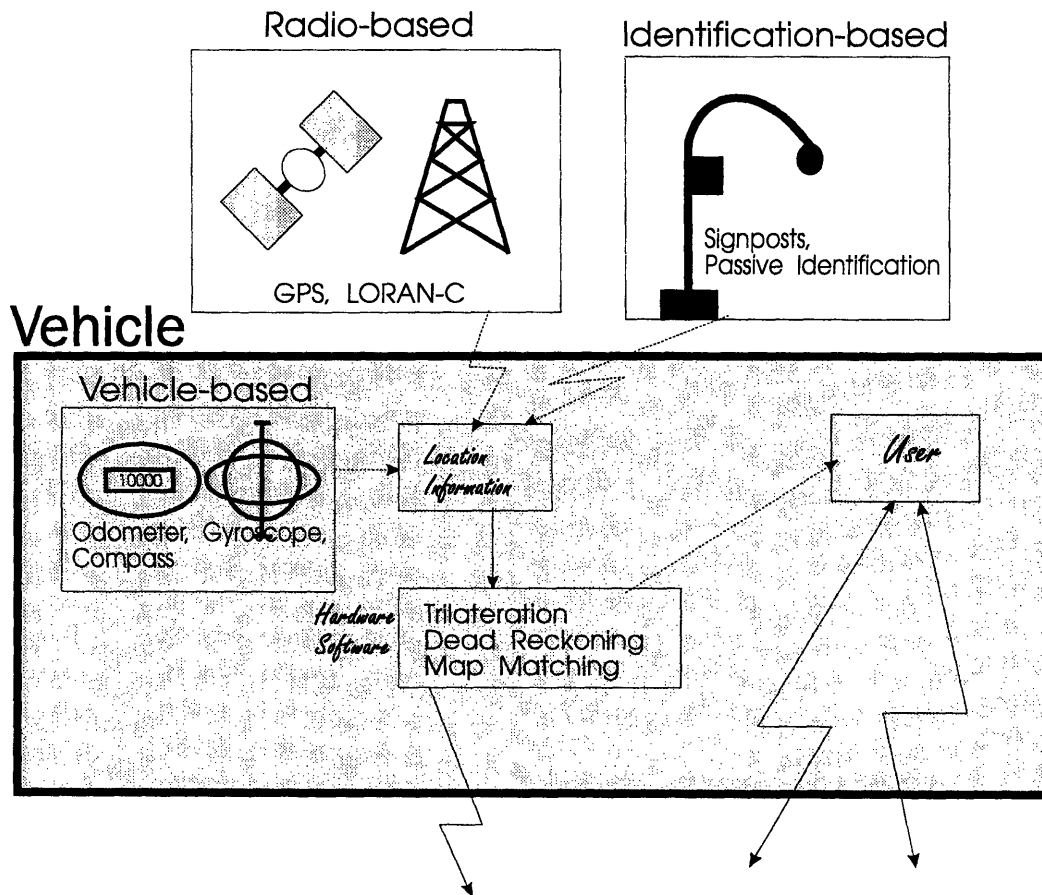
3.3.1 Odometer

Odometers were the first technologies to be tested for AVL systems. Almost every vehicle out on the road today is equipped with an odometer that monitors an axle's rotation to measure how far that vehicle has travelled. Differential odometers that have sensors on both wheels of an axle rather than just one can provide more precision than ordinary odometers but are also more expensive. Odometer systems simply automated and recorded these readings. Odometer readings would be automatically collected and reset at the beginning of each trip. The odometer would also be linked with a timer, and in this configuration, as long as the route remained fixed, relative locations and times could be collected for the vehicle.

This technology was fairly inexpensive, but it had many drawbacks, the largest one being accuracy. It was not uncommon for these devices to be quite inaccurate due to wheel slippages and the fact that buses do not travel in a straight line, and for the purposes of transit operations, the accuracy was viewed as unacceptable. Also, odometers could only measure relative locations, thus if a route changed, the new route would have to be surveyed so that the relative locations could be "mapped" to the absolute locations. Also, if vehicles went off-route, all location estimates collected afterward would be incorrect since the system assumes that vehicles stay on-route. For these reasons, simple odometer sys-

tems are not considered for new AVL applications. Odometer systems were used as early as the 1970's by agencies like OC Transpo, but are not used as a sole method for location determination anymore.

Figure 3.2: Alternative Location Technologies



3.3.2 Dead Reckoning

Dead reckoning technologies were developed to try to increase the accuracy of odometer systems. Dead reckoning algorithms use measurements produced by distance and heading devices located on the vehicle to compute the vehicle's location relative to a known starting location. The distance devices are usually in the form of electronic or analog odometers which record wheel rotations. The heading devices can take the form of magnetic compasses or gyrocompasses and there is a wide variety to choose from. By adding heading devices, Dead reckoning improved locational accuracy to the point where accuracies became more acceptable.

Dead reckoning devices do not cost very much (Hamilton [34] estimates costs of Dead Reckoning systems to be about \$1500 per vehicle), but errors accumulate with distance travelled, so unless the devices are reset occasionally, they can become grossly inaccurate (Hamilton[32] estimates that errors can be on the order of about 1 - 3% of the total distance travelled). Dead reckoning technologies, however, have proven themselves in the field. Field tests of these technologies have been done as early as the 1970's and have been in regular use in a few agencies (Hannover and Wiesbaden in Germany and Hamilton, Canada to name a few [28,58]) for the past few years.

3.3.3 Signposts

In a signpost system, roadside proximity beacons (signposts) are installed along routes. These signposts emit their ID at a certain radio frequency which is detected by the bus as it passes. With the signpost and vehicle ID known, the bus can thus be located to the last signpost passed. If control is centralized, location data is then usually sent from the vehicle to a central location through wireless transmissions.

Another technology related to signposts is passive identification. The accuracy and resulting output of location is the same as signposts, but the techniques for location are slightly different. Here, readers which emit radio signals are placed along the route and when a bus passes, the reader reads an identification “tag” that is attached to the bus. The reader information and the bus tag information are used in combination to determine location. The technology is somewhat analogous to bar code readers seen in many grocery stores. If this data is needed at central control, it would usually be sent through land lines connecting the readers and central control. For the purposes of this thesis, both types of systems will be referred to as signposts.

The accuracy of signpost technology is dependent upon the density of signposts along the routes, but accuracy is excellent where the vehicle passes by the signpost and location is absolute. In order to calculate locations, the absolute locations of the signposts need to be known. Between signposts, however, there is no information about location, thus accuracy gradually decreases until the vehicle passes the next signpost.

Signposts are a fairly expensive option both in terms of capital and maintenance costs. Gomes et. al. [33] estimated signpost equipment to cost about \$3500 per vehicle and \$1000 per signpost. A more recent cost estimate from London Transport [Director 30] estimates signpost costs to be about 2,500 pounds (\$1700) per vehicle and 1,000 pounds (\$700) per signpost. Signposts are also somewhat inflexible since if a route changes, all the signposts associated with that route must be moved to the new route, although signposts which are portable serve to mitigate this problem. Signposts are a relatively reliable technology that has been proven in the field with the history of signposts about as long as dead reckoning technologies, and there are many agencies who are currently utilizing signpost technology (TTC, OC Transpo, Seattle to name a few).

3.3.4 Global Positioning Systems (GPS)

GPS is a satellite-based radio positioning system made possible by the U.S. Department of Defense. A receiver on board the vehicle determines the vehicle's location from the radio signals sent by three or more satellites among a network of 24 satellites. When the GPS receiver receives signals from at least three different satellites, it will receive them at three different times since these satellites are at different distances from the receiver. Within the receiver, these time differences are converted to an approximate global position in a mathematical process called trilateration, which is accurate to about the nearest 50 - 100 meters.

Accuracy may be increased, however, by using a method called Differential GPS. In this method, an additional receiver is placed at a known fixed location in the system and all moving receivers use the information from this fixed receiver in addition to the satellite signals to gauge their positions. With Differential GPS, it is now possible to locate vehicles to the nearest 5-10 meters, so GPS is potentially a very accurate technology (Hamilton[34] and Gomes[33]). GPS is able to determine the absolute world co-ordinate positions of the bus which permits determining bus positions on routes that are not fixed or for buses that go off route.

The two main disadvantages with GPS are its relative novelty within the industry and its potential problems within an urban environment. Since GPS is a relatively new technology, it has yet to prove itself in a real-life transit application although it has been successfully applied in the police, ambulance, taxi and trucking industries [McLellan 44] for dispatching and location purposes. These industries, however, do not have transit's problem of maintaining high frequency regular service in an urban environment. Some cities, notably Denver, Dallas, Milwaukee and Baltimore [State of the Art 57], are currently test-

ing GPS systems. The second main disadvantage of GPS is the potential for urban structures like high buildings and tunnels to block out the signals from the satellites, so if a vehicle's route is impacted by these structures, it's locations can be lost for a time. This phenomenon is known as the "urban canyon effect". There is no charge for using the satellite signals and the GPS box itself can cost as little as \$800 to \$1000 a unit. [Gomes 33 and Stone 66].

The hardware requirements for a basic GPS system are relatively small. Essentially, all that is needed is the GPS unit that receives the signals and performs trilateration to determine its position. The software requirements vary depending upon the sub-systems that are linked up with GPS, but a basic requirement includes the trilateration algorithm programmed inside the GPS unit. Software outside the unit is programmed to process the location data. More advanced software is needed to handle communications and corrections if Differential GPS is utilized.

3.3.5 LORAN-C

LORAN-C works on the same basic principle as GPS, only the transmitters are ground-based antennas instead of satellites. Again, only receivers are necessary since the network of antennas have already been set up. This technology is less advanced than GPS technologies and is also less accurate, typically providing location to about the nearest 100-200 meters (300 -600 feet) [Hamilton 34]. As with GPS, however, techniques like differential LORAN have been used to improve accuracy to up to 30-40 meters.

LORAN-C, like GPS, also suffers from the urban canyon effect, although LORAN-C in general seems to maintain better signal locks than GPS in urban areas. LORAN-C loses signal locks when the units approach power stations and GPS systems encounter trouble near areas of heavy foliage. Whereas GPS has complete coverage in the U.S, LORAN-C

covers most of the east coast and west coast, but is deficient in the south-central part of North America. In spite of these shortcomings, this technology has had more applications in transit use since the technology has been available for a longer time. Small cities like Champagne-Urbana, Illinois and Sheboygan, Wisconsin have been using LORAN-C to monitor and control their vehicles. The basic cost of a LORAN-C receiver is about the same as a GPS unit or a little bit more [Hamilton 34].

3.3.6 Map Matching

As a supplement to the other techniques, map matching techniques use computer algorithms to match the vehicle's actual path with that of the feasible path on the map to reduce any errors created by the other techniques. If a location system shows a vehicle's position is beyond any feasible path on the map (e.g. the locator puts a vehicle in the middle of a park), the algorithm will compute the closest feasible path and position and then will relocate that vehicle to that position. This technique is meant to complement, not replace, any of the other alternatives. The biggest advantage of map matching is that it needs no hardware. The disadvantage of it, however, is that it is software intensive and requires detailed map information. Unfortunately, data could not be found for map matching software costs, but they would definitely include the cost of obtaining accurately digitized maps.

3.3.7 Combinations

From the above discussion it is clear that some technologies are strong in some aspects of vehicle location (e.g. cost and experience in the field) while others are strong in some other aspects (e.g. accuracy and reliability). Since no single technology dominates, it may be advantageous to combine two or more technologies to exploit the strong points of each.

For example, odometer technologies are often combined with signposts to create a hybrid location technique commonly called signpost-odometers. In this configuration, signposts would serve to reinitialize the distances measured by the odometer every time the bus passes a signpost. This configuration strengthens the accuracy weaknesses of both technologies. Odometers give you reliable location information between signposts and signposts serve to correct the cumulative errors associated with odometers. This configuration is hardware intensive, however, and thus relatively costly. You need signposts, odometers and the hardware and software necessary to integrate the relative locations of odometers with the absolute locations of the signposts.

Dead reckoning can also be combined with map matching algorithms to give more reliable location data. The dead reckoning technology is able to tell when a vehicle turns a corner or how far a vehicle has traveled and the map matching algorithm is able to use this data to tell where on the map the vehicle should be.

Another combination is GPS technology with dead-reckoning technologies. GPS systems give good absolute positions, but may have problems in local urban environments while dead reckoning technologies give good relative positions and work well in urban environments. Combining these two would give locations that are accurate from both a relative and absolute perspective and also gives a system that works well in an urban environment. With any combination of technologies, however, the complexity of your system increases and so does the cost.

3.3.8 Comparative Analysis

These technologies were compared by Hamilton [34], Gomes et. al. [33], Stone [66] and London Transport [30] with the integrated results shown in Table 3.1.

From the descriptions of the relative strengths and weaknesses of these technologies, it is clear that some trade-offs have to be considered when choosing a single technology. The most proven technologies are signposts, odometers and dead-reckoning, but they are relatively old technologies and they may be as expensive as, or even more expensive than the newer technologies such as GPS, which still are relatively unproven but show great promise.

The average prices do suggest that radio navigation systems like GPS (and LORAN-C) might be cheaper than the older technologies, but these prices might be misleading in that the unit costs listed are for units that were installed for applications other than transit. To configure these newer technologies to be compatible with transit's requirements might prove more costly than the more established technologies at least during the pioneer applications. In a survey of transit agencies conducted in 1991, one third of them said that they would choose signposts and one quarter would choose GPS if they were to select a location technology at that time [Levinson 40].

In terms of accuracy, the combination technologies are the most accurate, but they also may prove to be the most expensive. It also seems fairly safe to assume that any system that needs a high degree of accuracy should consider combination technologies since all individual technologies have an accuracy weakness of one kind or another. Many transit agencies have expressed a need for locational accuracy to within about 50 meters as an absolute minimum accuracy. For example, Baltimore's previous LORAN-C requirements required an accuracy of 45 meters [Hamilton 34]. Some agencies, like OC Transpo, however, only wish to know locations at discrete intervals, thus a strict signpost system was an appropriate choice for them.

Location Systems	Accuracy	Constraints	Costs		Reliability
			Onboard Equipment /Vehicle	Additional Costs	
Autonomous Systems					
Dead Reckoning	tens of meters or about 1-3% of distance traveled	error accumulation	approx \$1500 - \$3000	comm. system + related SW ^a	N/A ^b
DR with Map Matching	tens of meters but reliable	high costs	\$550	comm. system + related SW + maps	Proven technology
Proximity Detection	few meters when combined with Dead Reckoning	high costs for off-route applications	\$1700 - \$3500	infrastructure \$700 - \$1000/signpost + comm. system + software	N/A
Non-Autonomous Systems					
GPS	50 - 100 m, theoretical 5m with Differential	low update rate	\$700	comm. system central facility	Uncertain, urban canyon effect
LORAN-C	300 - 600 ft	atmospheric conductivity noise interference	\$700 - \$1500	comm. system + related SW, ~\$20000-\$50000 for base	Mostly Proven Technology
REVLOR	30 m	multipath problems	\$500 - 600	infrastructure + SW; service charge	

Table 3.1: Broad Analysis of AVL Systems for Urban Applications

a. SW: Software, REVLOR: Reverse LORAN, DR: Dead Reckoning

b. Not Available

3.4 Communications Systems

Data on vehicle locations are useless for real-time applications unless they can be sent to the appropriate end users quickly. Communications systems which transmit vehicle location information to a host system for processing are thus the “backbone” of most systems. Communications systems are also crucial in linking the primary users of the system, including operators, controllers, inspectors, and passengers.

This section describes some of the physical media across which data and voice communications can be sent, and lists some strengths and weaknesses of each medium, focusing on cost, reliability and availability. The technologies that are looked at include cable/

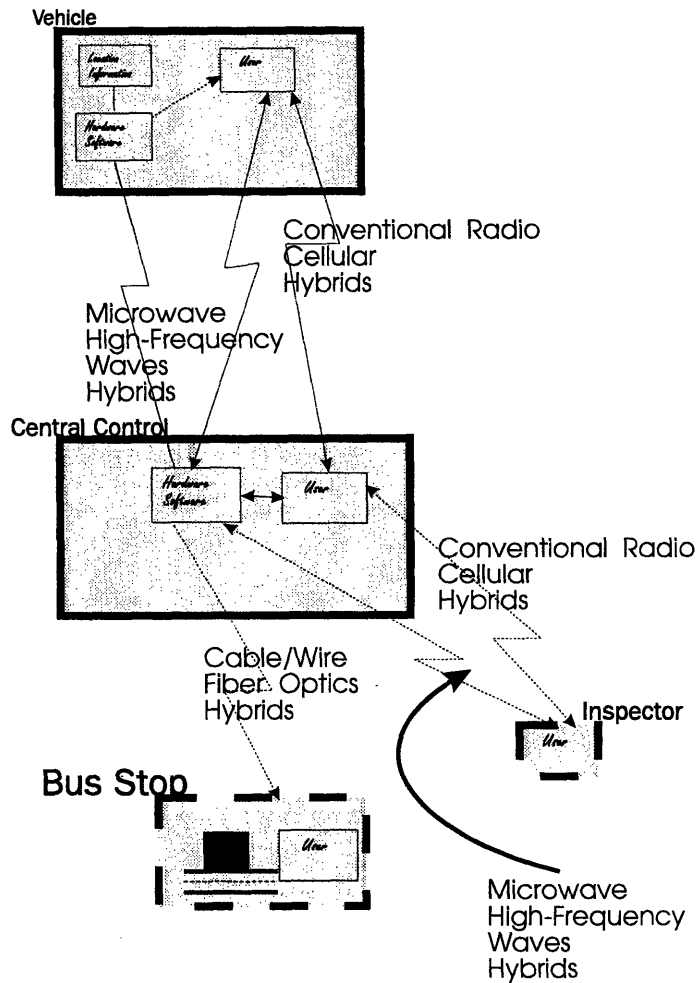
wire communications, conventional radios, microwave communication, cellular communications, spread spectrum systems and other hybrid technologies.

A common issue with most wireless technologies is wave saturation, where many users are competing for the use of limited bandwidth for their communications. Bandwidth capacities are quickly being filled creating a serious problem in large transit system operations. One of the reasons for this problem is that transit's central control systems often demand frequent information from its vehicles. In most centralized systems where a fleet of vehicles is to be controlled, many vehicles have to be monitored at once, which means that communications channels cannot receive locations from one vehicle continuously.

Generally, this problem is dealt with using a round-robin approach called "polling" which takes location data from one vehicle at a time over one or several communications channels. The more frequently a vehicle is polled, the more accurately its location is known. Except for exclusive passive identification systems which do not normally utilize polling, but transmit whenever a vehicle passes, polling rates and polling control is usually conducted independent of the location technology. The more frequent the polling, the more demand is imposed on the channel. Another reason for channel saturation is that there is still heavy reliance on voice communications between controllers, operators and inspectors in order to maintain performance which uses channel capacity inefficiently.

The overall roles for communications technologies in an AVL system and the possible technologies that can fill these roles are shown in Figure 3.3.

Figure 3.3: Alternative Communications Technologies



3.4.1 Cable/Wire

Wire/cable communications are the most reliable media for communication. Unlike wireless communications, you do not have to fear interference from the atmosphere or from other wireless messages. The main disadvantage, though, is obvious: it is impossible to build an AVL system using exclusively wire or line communications since they cannot work with mobile units. You have to have some form of wireless communications to and from the vehicles. It is possible to use wire/cable communications for stationery parts of the system, such as bus stops and train stations for passenger information, or at signposts

to relay information back to a host computer. Relying on fixed lines even for these purposes has some drawbacks however. You have to install new wire each time you wish to expand your system or change routes which can be quite expensive.

3.4.2 Conventional Radio

Standard radio communications are the oldest type of wireless communications used for public transportation having been used to help regulate bus routes for well over 20 years. Radio equipment has been installed in vehicles, control centers and inspector positions so that operators, inspectors and controllers can maintain contact with each other to alert all parties to emergencies, unusual conditions in the field and control decisions. Standard radio communications are probably the least expensive and most widely used form of communication in the industry.

Radio communications can be transmitted on a variety of carrier waves in the VHF and UHF bands and probably the most popular type is through FM transmission. Bandwidth and power output is regulated by the FCC however, thus the number of channels available for operator and controller is extremely limited. This is especially true in urban areas where demand for limited bandwidth is great and in some cases, agencies are forced to share AVL channels with other users [72].

Wireless radio communications are also not the most reliable systems, being vulnerable to atmospheric and urban interference problems which can result in unclear reception, and it is even possible that transmissions can be mixed up. The quality of reception problem may be mitigated by the use of digital radio communications, which usually provides clearer reception. The cause of poor sound quality during analog transmission is noise and distortion that is added every time the signal is processed or relayed. Since analog signals

may be processed 30-40 times as they move from source to destination, the resulting signal may look very different from the original signal.

Digital radios, however, take analog waves and convert them to digital signals, which are sent to another digital radio where the receiving equipment converts the signal back to voice waves. In this scheme, a lot less distortion occurs during processing since more interference is allowed before an “on” signal is incorrectly interpreted as an “off” signal and vice-versa [Weisz 69]. The result is a much higher transmission quality.

3.4.3 Microwave

As frequencies increase from the VHF and UHF bands into the microwave bands, several factors affecting the quality, costs and characteristics of transmissions change. First, as frequencies increase, background noise is reduced, generally resulting in higher quality transmissions with less distortions and errors. Second, power requirements and thus cost of transmission increases. There is thus a natural trade-off that exists between quality of transmission and cost. Third, the wave signals become more line-of-sight oriented and are less affected by atmospheric conditions which can curve and bounce back lower frequency waves. This has two effects: higher frequency waves transmit over much smaller areas because their signals break through the atmosphere rather than bounce off it, and higher frequency waves are used more for line-of-sight transmissions than for general area use [Weisz 69]. This is one of the reasons behind radio-navigation communication technologies like GPS transmitting over high frequencies of between 1 and 2 GHz.

The specific frequency which is to be used also determines the size and types of antennas required and the data speed rate of transmission. As frequency increases, the required size of the antenna decreases, so although low frequencies can transmit over longer ranges, they require large antennas up to 8 feet high operating over large metal surfaces

(up to 16 feet diameter). On the issue of transmission speed, the FCC has constrained the 40 - 512 MHz range to transmit at a maximum of 3,600 baud (bits per second), while frequencies above 512 MHz can transmit at faster speeds. The transmission speed directly determines polling rates, thus transmissions at higher frequencies allows for faster polling rates [72].

These characteristics of higher frequency microwaves make them attractive for some transit applications. The “line-of-sight” characteristic of microwaves makes them useful for location technologies such as signposts, GPS and passive identification technologies. In all of these technologies, a “beam” is directed at the vehicle and information either is “beamed” back or retained by the vehicle. These location systems must also be free of distortion and error, which also suggests using higher frequencies.

Since microwaves are less subject to distortion, they are also sometimes seen as an alternative to conventional radio frequencies for voice communications use. Some digital radio networks operate over the microwave bands, but the limitations of cost and effective range of transmission limits its use.

3.4.4 Cellular

Cellular technologies are one of the newest of this subset of technologies. Cellular technologies divide the territory up into “cells” in which the entire bandwidth is localized to a particular cell area, controlled by a cell station. This is done by using multiple antennas each transmitting at relatively low power. By dividing the territory up into cells, a frequency can be reused in non-adjacent cells, thus boosting the overall capacity of the communications system and lessening the effects of wave saturation. All vehicles in a particular cell share the frequencies that are controlled by that antenna. When a vehicle moves

out of the cell, communication is automatically switched into the next cell, providing a seamless flow of communication [Lalonde 38].

Many large telecommunications corporations have used this technology to build reliable publicly accessible wireless cellular telephone networks. These cellular networks cover many urban areas, and usually offer the same sound quality as wired telephone communications. Two of the reasons for improved sound quality are the improved technologies that have been developed for the equipment (the companies wanted quality comparable to wired telephones to compete effectively in the market) and the higher frequencies used (approximately 800 MHz).

The widespread availability of these networks in urban areas makes it an attractive communications option for many transit agencies, since it does not have to be custom designed for the transit agency. There are some drawbacks to using this technology, however, notably cost. Transit agencies have to pay a certain rate for every minute that they use a cellular telephone line and it can become quite expensive for the agency. For this reason, many agencies that have been using the cellular network have been using them mostly for backup purposes in case the main systems fail. The Toronto Transit Commission (TTC) is one example of this usage.

3.4.5 Spread Spectrum Systems

The State of the Art [57] describes this technology the best:

The concept of Spread Spectrum is simple. Rather than operating on a single frequency, Spread Spectrum systems transmit a low power signal with the information to be transmitted distributed over a band of frequencies. "Receiver intelligence" is used to decode the information.

With Spread Spectrum systems, agencies no longer have to use dedicated spectra for communications. Instead of being primary users of one spectrum, they may become secondary users on a non-interference basis of several spectrums which may reduce licencing costs and increase overall channel capacity. This technology is relatively new, however, and may not be widely available. There are no recorded examples of transit agencies currently using Spread Spectrum technologies.

3.4.6 Hybrids

Many types of technologies have been developed to solve the wave saturation problem and to increase the clarity of wireless communications. Channel splitting techniques effectively split an assigned bandwidth into multiple channels which can carry either voice or data. This technique gives you more channels, but it reduces the rate at which data can be transmitted and the type of modulation that can be performed. There is also some concern about adjacent channel interference [Lalonde 38].

New modulation techniques have also been developed that permit higher speed data transfers, thus lessening the time required for a message to occupy a channel. New developments in modulation, like ACSB modulation permits voice communication over a 5 kHz channel instead of the standard 25-30 kHz requirement, thus it is possible to split one standard channel into 4 or 5 [RMS 54].

Currently many radio communications are being done in semi-duplex mode in which information goes back then forth in a serial fashion over a single communication channel. Full-duplex radios allow communications to occur back and forth simultaneously, thus reducing radio cut-in time. While full-duplex radios are expensive, their costs are expected to be reduced due to heavy competition from other communications technologies.

3.4.7 Comparative Evaluation

From this brief review of the alternative communication technologies, it is obvious that there is a lot to choose from, including many technologies which are quite new. The problems of wave saturation and reliability reduces the long-term prospects for standard voice radio communications in urban areas, even though it is possibly the cheapest of all the alternatives. A lot can be done with the frequencies used for radio communications, however, much of it using software and hardware that splits, time shares or enhances transmissions on a bandwidth to achieve higher quality reception or lower required bandwidth for transmission. This is a case of substituting software and hardware for channel capacity. Of course, these advanced options increase the cost of the system, but that may be inevitable in a capacity constrained system.

In terms of availability, standard radio communications systems are the most available mostly due to the fact that they have been around the longest. Cellular technologies are also widely available in urban areas and microwave technologies are available for higher quality transmission, but at an added cost. Digital radios are still a relatively new but growing concept and this may make microwave frequencies widely available for voice communications in the near future. Spread spectrum technologies, though not currently available, may be available in the near future. The hybrid technologies vary in terms of their availability.

One important point to note before closing the discussion on communications systems is that technologies that increase capacities are not necessarily the best answer to the wave saturation problem. Another approach that deserves consideration is the reduction of data and voice communications transmitted over the frequencies without loss in performance. This is done by either instituting policy regulations to eliminate unnecessary communica-

tion or developing software to “time manage” the communications so that communications at peak times are either avoided or re-routed efficiently. Polling rates are also an issue where channel capacity is concerned, and there is a clear trade-off here. If vehicles are polled less frequently, demand for capacity is reduced, but so is the accuracy in vehicle locations. One must decide what is an appropriate polling rate to satisfy both accuracy requirements and communication constraints.

3.5 Hardware and Software

This category presents by far the widest array of alternatives. Not only do you have to decide upon the types and sizes of computing machines and accessories, you also have to decide how they will communicate with each other, what the function of each machine will be and which machines will keep track of what data. Hardware plays many crucial roles in AVL systems and there are many issues involved when making hardware choices. Software is also of critical importance. Without the software, the hardware is useless, and software is included in almost every subcomponent of any AVL system.

Hardware and software provide essential links between the users and the machines. The system must be relatively easy to use and understandable by all users, but must also provide useful information. Hardware and software is also used to collect data, and process the data into more usable and perhaps more accurate form. Hardware is also used to store and output data on demand either to video or in hardcopy for management and controller reports. The overriding role of hardware and software, however, is to manage and control the entire system and the flows of information.

Some key issues in hardware and software design involve cost, location, system structure and performance.

Location

The location of hardware and software refers to the level of centralization of data processing and control, which is an important issue that directly impacts cost, performance and required user interfaces.

In a centralized system, most of the data is processed at a central location, with inputs coming in from multiple vehicles and other sources. In this configuration, the equipment on the vehicles does not need to be that powerful, but the hardware and software at the central location needs to be very powerful and the programming needs to be efficient and sophisticated.

In a more decentralized system, more processing is done on the vehicles, thus reducing the communication demands as well as the need for a powerful system at central control. In this type of system, the operator gets some information directly from the on-board equipment, bypassing the control center. In this configuration, the programming and hardware installed on board vehicles needs to be more powerful and more sophisticated.

Buses that have advanced processing capabilities are referred to as Smartbuses. Decentralized systems should also have more advanced interfaces on buses than centralized systems and they should have some level of storage and output capabilities. In this configuration, much of the control and decision making is left to the operator, which may or may not be a good idea as will be discussed in Chapter five.

System Structure

When a hardware and software system is being designed, care must be taken in making sure that the system is flexible and can accommodate changing information needs, changing system requirements and changing technologies. With AVL systems taking a long time to implement (the TTC took 15 years to develop fully its AVL), changes are inevitable. If a transit network expands in size over the development period, expanded

hardware and software requirements may be needed and the agency should provide extra capacity to satisfy these needs. Similarly, if new technologies become feasible during the development period which the agency wishes to adopt, the system should be structured such that new technologies can be easily introduced.

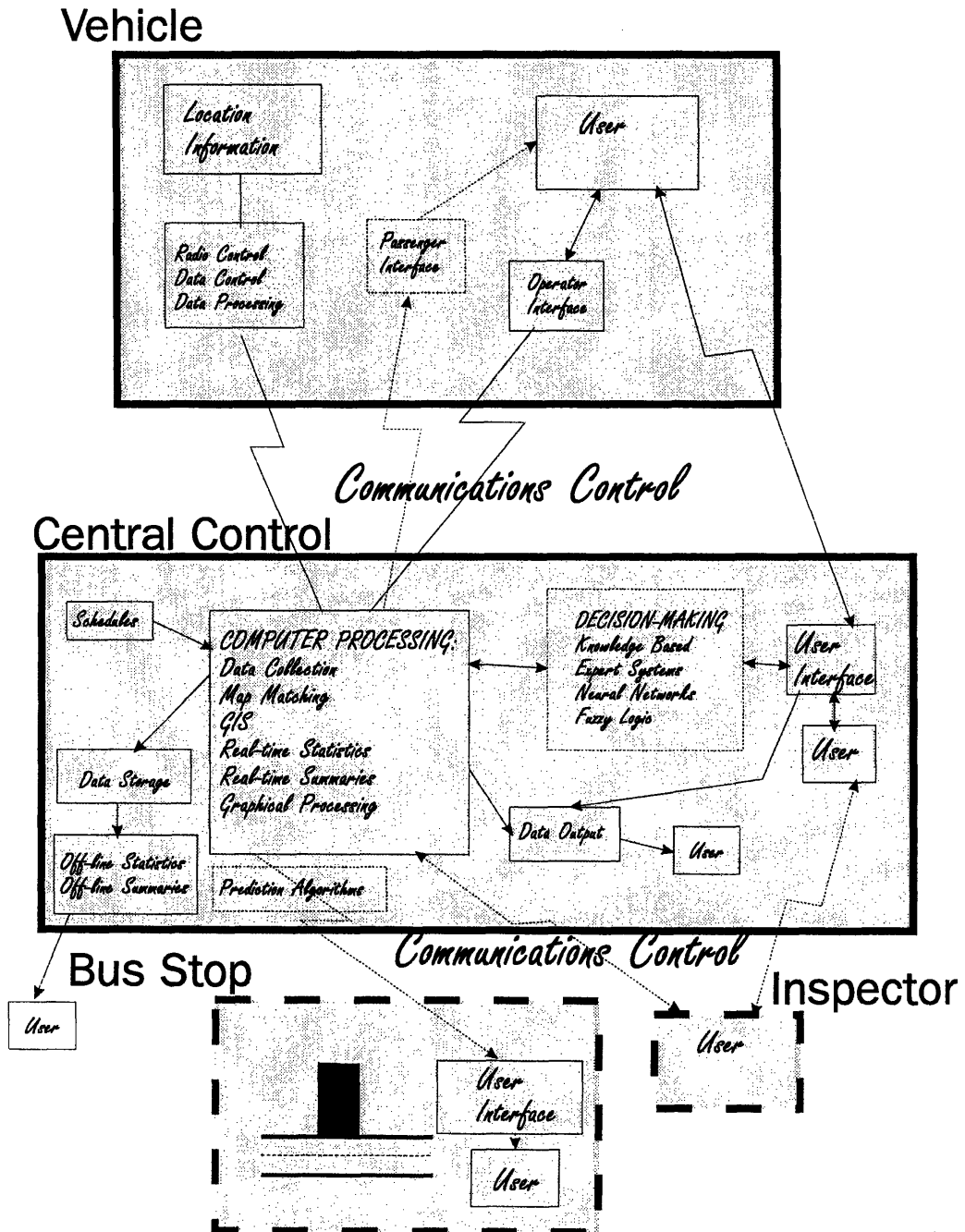
The resulting system structure should thus be flexible and modular in design. A modular design breaks up large systems into more manageable sub-systems that have connections with each other, but otherwise can operate independently. If a change in a sub-system takes place as a result of changing system needs or changing technology, ideally only the sub-system needs to be changed. A system that is not modular in design would need to undergo a more extensive revision process in order to accommodate the change. OC Transpo has followed the philosophy of modular design in their systems with success. In their APC system, technology has changed several times since APC's inception, but modularity in design has enabled OC Transpo to retain most elements of their APC system.

Figure 3.4 shows the roles of hardware and software within an AVL system. Other issues that affect hardware and software design are discussed below.

3.5.1 Collection and Processing of Data

Over time, computer technology is steadily becoming both more powerful and less expensive. Processing speeds are increasing and physical sizes of systems are decreasing. It is within this environment that transit authorities are making their computer hardware and software decisions. Large transit systems may collect and process incredible amounts of data, including location data for all vehicles and possibly supplementary data such as passenger and vehicle status data to name just two.

Figure 3.4: Hardware and Software Components of an AVL System



The agency needs to choose hardware that tailors the computer system capacities to the demands that will be placed on it. Software compiles and converts data gathered by the AVL devices into usable form for the end users. Software may also enhance the AVL data. For example, error checking algorithms serve to minimize the errors associated with the AVL data to make the locations more accurate and algorithms may be used to predict locations of vehicles at future times. London Transport employs such algorithms for its passenger information system as will be discussed in Chapter 4. This information can also be used to “fill in the gaps” in information between polling times where no information is given about vehicle locations.

3.5.2 User Interfaces

Hardware

The hardware involved in user interfaces must take into account the functions of the users and ergonomic issues. Information displays need to be readable and clear and input devices need to be effective and efficient. All hardware needs to be at the right heights, angles and distances so that the users can comfortably make use of these devices. On vehicles, user interfaces must be sufficiently unobtrusive so as to not interfere with normal vehicle operations. Hardware systems also need to respond quickly to user inputs so that the users can perform their functions efficiently [Stearns 62].

Software

Software is also a very important element of user interfaces. The information that is displayed needs to be processed in such a way that it is readable, easily understandable and gives the users the relevant information needed for them to perform their duties. The software must also allow users to switch tasks in a seamless manner. In the control rooms, these devices are usually more powerful, give more information and allow the user to per-

form more functions. On board vehicles, the interfaces are usually smaller due to space constraints and their functional requirements which require less equipment than at the control centers.

Decision-Making

User interfaces can also affect the roles that users play in the system in the aid they provide to their decision making. Software can be programmed to analyze the real-time data to present suggestions to aid controllers in their decision making. There are many possible ways of approaching this task including knowledge based expert systems, neural networks, fuzzy logic and decision support systems [Allen 4 and Kosten 37].

Knowledge based expert systems utilize experts in a specialized field to aid in their implementation. When the experts are presented with a scenario, they identify the appropriate solution. An almost exhaustive list of scenarios are programmed into the software in this manner so when a real situation occurs, the software will select a strategy based on the rules previously formulated by the experts.

Neural networks are programmed so they “learn” about correct procedures over time. Through continually giving inputs of possible problems and then giving the algorithm the correct solution, over time the neural network develops and learns the correct procedures for a more general problem. The more cases and observations that are presented to the neural network, the more calibrated the network becomes and the more likely the network is to make correct decisions.

Fuzzy logic rejects the concept of absolute calculations and measurements but instead makes its decisions based upon calculations and measurements that have a range of answers to them. In an imperfect world where little is known with certainty, fuzzy logic can solve problems that were impossible to solve before using absolute calculations. Since operations control is also an inexact science, fuzzy logic may well be applicable.

Decision support systems utilize a much simpler concept than the previous three programming styles, and unlike the other styles which are still largely in conceptual stages, decision support systems can be utilized immediately. Programming consists of selecting a decision given a limited set of decision rules based upon the state of the system. An example would be a decision rule that suggests short turning a vehicle if the preceding headway is less than X minutes. Although the rules themselves may be arbitrary and may not yield the best results in all cases, it is the simplest of all the listed programming types to utilize. Decision support systems can be thought of as a simplified form of a knowledge-based expert system.

One important issue that must be discussed is the role of the human once the software is able to make decisions. Traditionally, humans make all of the decisions, but in this new environment, software can play any role from simply suggesting decisions to fully controlling the decision-making process. The preferred role of humans in decision-making can be decided by examining the relative efficiency and effectiveness of decision-making under each alternative.

3.5.3 Storage and Output

Before and after information is processed, it needs to be stored in both volatile and non-volatile memory. Like other computer components, computer memory is also becoming less expensive, but more memory still implies greater cost. Memory can also affect performance as many types of software utilize available free memory to increase performance. Transit agencies have a myriad of memory devices to choose from, including hard drives, floppy drives, optical drives, RAM chips, tape backups and many more.

Occasionally, hard copy output about the system is generated and analyzed by the users of the system who can include controllers, planners and managers. Choices need to

be made on the types of output that are to be generated including real-time and non real-time performance.

3.5.4 System Control

By far the most important role of hardware and software is to control the AVL system in an efficient manner. This includes seamless integration of all the AVL subsystems including location systems, communication systems, user interfaces, data processing, reporting and storage systems and the users of the system. Location data, if collected through polling, needs to be routed efficiently into the systems that stores and process this data. Communications between users needs to be managed and controlled such that messages get to their intended destinations in an acceptable time period. Inputs into user interfaces need to be interpreted correctly, processed and results output to the requestor in a reasonable period of time. Finally links integrating all these systems must be established and maintained so that the entire system runs with as few flaws as possible. The choices of system software and hardware to integrate all of these systems are important ones, since they will directly affect the performance of the AVL system and also makes up a large proportion of the total costs.

3.6 Human Factors

In a discussion that is filled with components and issues of a technological nature, it is easy to lose sight of the users who will have their roles changed as a result of these technologies. Nevertheless, it is essential to consider how best to integrate users into a new system which might actually mean changing the nature of some components of the systems to suit users needs.

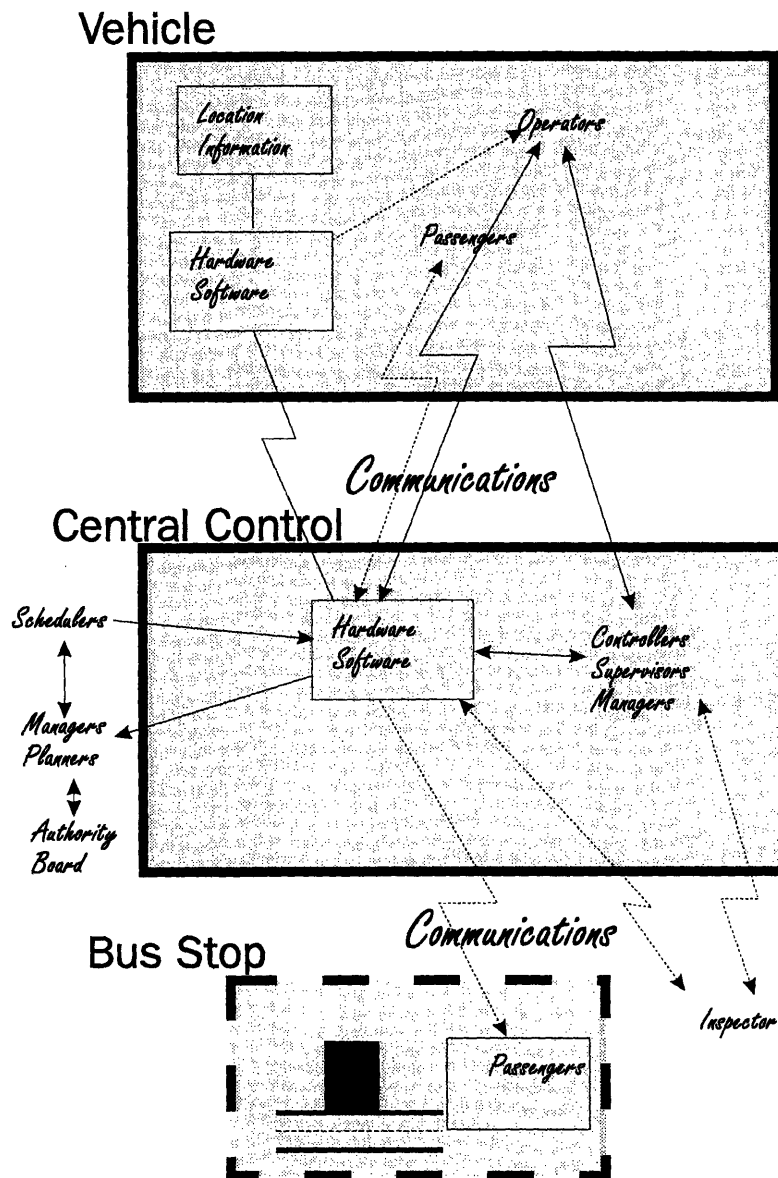
One may wonder why effort needs to be placed on human factors. Is it not the goal of these systems to reduce the need for manual monitoring and control, and thus doesn't the debate on human factors become irrelevant? This may be true in the long run, but until the time comes when transit systems can operate without the need for any human input, the human element will remain a vital part of these systems. It may be possible to replace a few positions with these new systems, but the bulk of the human input will still be just as essential as before. This is because AVL systems are primarily designed to aid the humans that use them. While AVL systems have the potential to become valuable tools for these users, they are just that - tools. Without tremendous leaps in technology, it would be impossible for these systems to replace the humans using them.

The roles of humans under an AVL system, however, can be expected to change, sometimes slightly and sometimes dramatically. Human factors research serves to study what these necessary changes will be and the best way in which these changes can be made.

One obvious issue in the human factors debate is the role that humans will have in a new AVL system. A transit system is made up of many types of positions; operators, inspectors, controllers, passengers, managers, planners and schedulers. All of these positions will be somewhat affected by the introduction of an AVL system and this section will look at these positions and their roles in an AVL scenario. This section will also look at some roles that might be created as a result of AVL systems. Another issue concerns the training that is needed for people to make a smooth transition to a new system. A third issue involves possible labour savings that can be realized by automating some parts of the system that was previously done manually.

Figure 3.5 shows how human roles are potentially affected by an AVL system.

Figure 3.5: Human Roles in an AVL System



3.6.1 Operators

Operators have always had final responsibility for their own buses. Except for occasional instructions from the controllers or inspectors, it was up to the operators to maintain

their schedules as well as operate their buses safely and courteously. These new AVL technologies are capable of aiding them in schedule maintenance by keeping track of how early or late they are. Operators can also reach controllers more easily with a more advanced communication system.

In addition, these technologies can give operators the extra role of being community watch dogs: any incident that is observed by the operator can be directly relayed to the authorities. These technologies may also make the operator's job a little safer. With silent alarm features, any dangerous situation that occurs on the vehicle can be resolved more quickly with a better chance of a safe outcome. These new roles are relatively cosmetic ones, however; the operator's primary role will continue to be to operate their vehicles safely and courteously.

Depending upon the system that is installed, operators can be called on to perform many or no extra tasks. Their primary objective, though, does not change and no extra task should be imposed that could possibly jeopardize that primary objective. There may also be labor contract agreements that constrain the number of tasks that an operator is required to handle. With relatively few changes in operator roles necessary, there should not be too much training necessary, but some form of training should be provided nonetheless.

Currently, the operator usually has a very small input into the control process. This is somewhat unfortunate since operators have the most complete knowledge on local conditions which could serve as a rich source of information for real-time control decisions as well as operations planning decisions. A new AVL system could take advantage of this by giving the operator more input into the control process and perhaps limited decision-making responsibilities. The issue here is the level of input and decision-making responsibility operators should have.

At the least, it seems like a good idea to give operators some ability to control schedule adherence by providing them with real-time schedule adherence information. If operators realize that they are off-schedule, they can perform their own controls like speeding up, slowing down or holding to get back on schedule. On low frequency routes which may be primarily controlled by schedules, primarily operator-based decision-making might prove to be effective in maintaining reliability.

Operators should not be the sole control decision-makers, however. Even if they are able to make good decisions at a limited local level for small disruptions in service (e.g. running late) or can make good decisions while operating low frequency routes, they still need instructions in cases of larger disruptions (e.g. road closures) from controllers who have system-wide information. Central control is probably also needed on high frequency routes that are more headway controlled rather than schedule controlled and where reliability involves interactions between vehicles. Chapter 2 showed that some control strategies such as incident mitigation and system-wide holding need the system-wide information that only central control can obtain. Even with the operators making some decisions, vehicles should still be monitored by controllers who should have the final say on multi-vehicle control strategies. The TTC provides schedule adherence information to its operators but still monitors and controls vehicles through a control center.

With AVL systems, operators can also provide more input into the control process, aiding controllers in their decision-making. What is needed is an effective communications system between controllers and operators that enable operators to report situations that they observe in the field.

3.6.2 Inspectors

Inspector positions are the ones that are subject to the most upheaval as a result of these new systems. Traditionally, inspectors were out on the streets recording times of vehicles and making control decisions based upon their direct observations. AVL systems would make their data collection functions unnecessary and as a result, some inspectors might be moved into the control room to make central control decisions as controllers.

This would be a natural evolution of their positions since they have already gathered field experience in controlling vehicles. Some inspectors would be left out in the street, but their roles would change. They might be used as extra helpers in cases of emergencies and may act as points of contact between the transit agency and the public. With AVL systems, inspectors can be used for different functions or they can be reduced in numbers. In any AVL scenario, there is probably the need for some residual street supervision. Service disruptions will still need to be attended to, AVL data will periodically need to be verified and controllers who work the control room would still need some experience on the street in order to understand field conditions.

The fate of the inspectors depends upon the objectives that the agency wishes to fulfill with an AVL system. They can either improve system performance by keeping inspectors and using them in more effective ways or they can save costs while keeping the same level of performance by cutting their ranks.

If inspectors are reassigned to the control room, they should undergo formal training to maximize their effectiveness in their new roles. Inspectors may have many types of backgrounds and many may not have any previous computer exposure. Since controllers probably need a rudimentary level of computer knowledge to perform their functions in an AVL system, it is essential that they get that training. Otherwise, the learning curve for

these people could be steep and it might take a long time before they become comfortable and effective within the new system.

After the TTC installed their AVL system, supervisory positions actually increased, but this was due to TTC policy that chose to retain supervisors and use them to increase service quality. Supervisors who initially were in the field now rotate between duties in the central control room and the field, performing control decision-making duties in the control room and providing emergency assistance in the field (see the TTC case study in Chapter 4).

3.6.3 Controllers

The role of the controllers is to take input data from operators and inspectors and make control decisions on vehicles in service and to respond to situations that arise in the field. AVL systems should give the controllers better information on which to base their decisions and as a result, they may approach their duties in a different manner, but in essence their roles would remain unchanged. They might become busier, however, since controllers would have to deal with the wealth of information that the AVL system provides them and since advanced communications systems may require more interactions with operators.

Controllers would definitely need some sort of training to become comfortable with a new AVL system, but the amount of training that is required for them should be less than the amount required for inspectors who come from the field. This is because controllers already have basic knowledge about what the system is supposed to do.

The number of controllers needed for an AVL system depends upon the amount of information provided by the system and the role it plays in decision-making. If the system generates more information without providing any decision-making assistance, more con-

troller positions may be needed to deal with the new information. At the TTC, controller ranks have indeed increased, but even with this increase, controllers still find their jobs more stressful because of the abundance of information they must assimilate.

Information overload can be minimized if software displays only the most important information to the controllers. Information overload can also be reduced if software assists in the decision-making process through programming methods such as knowledge based expert systems, fuzzy logic, neural networks or decision support systems. If this happens, the responsibilities of the controllers are changed: the more the system is involved in the decision-making process, the less the controller has to do and subsequently the more information the controller can assimilate.

If the system is able to make all decisions and convey them to the operators without any human assistance, controllers would become overseers who monitor the system to make sure that it is operating normally.

3.6.4 System Programmers and Supporters

The role of the programmer does not end once the system is fully developed. Even if the system is designed and programmed in the most efficient and effective manner possible, there will still be problems. Users will still require assistance to use the system even after their training periods are over, system crashes will still occur and hardware and software enhancements will still be needed. System programmers and support staff assume these roles after the system is up and running and they are often involved in the initial training of users. This is one position that is relatively safe from AVL-induced labor reductions: as the complexity of the system increases, there may even be an increased demand for system support staff.

3.6.5 Analysts and Decision-makers

Analysts and decision-makers take collected data, process and analyze it, and make recommendations to improve system performance. With manual data collection, analysts and decision-makers do not always have a rich or reliable source of data on which to base their analysis or decisions. The processing of data is often labor intensive and cumbersome. With AVL systems, the potential exists for analysts to produce better summaries and statistics given the better data that is collected. This may also relieve analysts somewhat from the burdensome task of processing information so that they can better concentrate on analysis and strategies for improvement. Decision-makers would benefit by having better and more reliable summaries and statistics in which to base their decisions.

Analysts, unlike controllers, do not necessarily need to learn the on-line aspects of the system, and since their backgrounds are usually more analytically oriented, formal training is often not required. They would need to learn some aspects of the system, however, such as the outputs it generates. As long as the AVL system does not actually do analysis, the need for analysts would remain unchanged, although their ranks might lessen if the system could be programmed to generate automatic reports and summaries that can be viewed and acted upon by the decision-makers.

The APC system at OC Transpo can produce reports automatically detailing many aspects of the agency's performance. The availability of these reports and the fact that they can be created as needed has given analysts and decision-makers at OC Transpo better knowledge of their system performance and better decision-making capabilities.

3.6.6 Passengers

The passengers are the ultimate target of any system since these systems are being installed to attract and retain passengers. Passengers are the ones who will ultimately determine the success or failure of these systems in the form of ridership increases or decreases, complaints or commendations.

Passengers using public transport make a travel decision, access a station, wait for a bus, board the bus, ride the bus and then alight the bus. With a passenger information system, it would be possible for passengers to receive information at various points in their trip. Based on this information, passengers can change their travel decisions or change their opinion of the system which may affect their future ridership.

The “inputs” that a passenger provides a passenger information system largely depends upon whether the system is passive or active. In a passive system, passengers do not provide any inputs; the information is simply displayed for them to see (or hear). This inconveniences passengers the least, but it assumes that all passengers want the same information, which may not be the case. In an active system, passenger must provide input such as pressing a button or touching a screen in order to receive information. Here, passengers have flexibility in choosing the information they want, but they initiate use of the system. An AVL system that directly impacts passengers should require simple interfaces to minimize the “training” that is needed for passengers to understand the PIS. A passenger that becomes inconvenienced due to the complex requirements of a PIS may choose to ignore the system altogether or even forego transit in frustration in the future.

Chapter 4

Case Studies

4.1 Introduction

Every agency that implements an AVL technology will be different in terms of goals, objectives and hence strategies for their systems. This chapter focuses on three agencies in particular - the Toronto Transit Commission (TTC), the Ottawa Carleton Transportation Commission (OC Transpo) and London Transport (LT). These three agencies were chosen because of their extended experiences with AVL systems, and because each agency adopted a different strategy in implementing the technology.

The initial goal of the TTC was to implement their technology to improve real-time operations control. In contrast, OC Transpo decided to use technology in a piecemeal fashion to improve their operating plan before introducing technology to real-time operations. Like the TTC, London Transport also focused on the real-time functions, but much of their emphasis has been on passenger information. The situation in London is very different from both Ottawa and Toronto in that the operating agencies are separate from the planning and policy agency which affects the ways in which these systems are designed and must function.

Each of these agencies are examined below including their goals, objectives and strategies for using technology. The systems that they put in place, along with their benefits and costs are also examined.

Since these three agencies have been developing AVL technologies for many years and many of their location technologies are relatively mature, agencies now in the process of implementing new systems are more likely to choose newer location technologies. This

chapter concludes by looking briefly at the experiences of several other agencies, including several that are currently implementing AVL systems using newer technologies.

4.2 Toronto Transit Commission (TTC)

4.2.1 Introduction

The Toronto Transit Commission (TTC) operates a multi-modal system with a largely grid-based bus network feeding the subway system. Most of the bus routes operate outside the central business district, while the two subway lines are focused on the CBD. The TTC also operates a large streetcar network also focussed on downtown.

In the 1970's, the TTC conducted a study looking into the service issues that the agency would be facing by the end of the century. The results indicated that increased ridership and street congestion caused by heavy population growth would place additional demands on the TTC to provide reliable and efficient service. Their existing manual procedures for service control would not be able to maintain the needed reliability and efficiency in the future, thus the report recommended that an Automatic Vehicle Location and Control (AVLC) system would be necessary. This prompted the TTC to start developing a centrally controlled integrated system that would serve to aid in many of their service functions. The system that was eventually developed is called the Communication Information System, or CIS [TTC 63].

This case study examines the TTC's CIS system first and then evaluating it. Prior monitoring and control systems are examined as part of the history of CIS, the location technology, communications, hardware and software behind CIS, the role of users and CIS's off-line capabilities. In evaluating CIS, the thesis analyzes the process of development,

installation and training, its costs and benefits and user opinions about CIS are all reviewed.

4.2.2 Prior Service Control Methods

Most of the information gathered about prior control methods at the TTC was obtained through interviews with TTC inspectors. Prior to the installation and utilization of the AVL system, the TTC obtained most of its information in a traditional manner. Passengers received information via static displays at bus and streetcar stops, through inspectors on the street, or through fare collectors at subway stations. Most of the control was done by inspectors out in the field with one or two inspectors assigned to strategic locations on a route.

The inspectors would sometimes coordinate with their local control centres principally relying on special telephones installed on light poles, but the majority of supervision was conducted in the field. The inspectors would note the arrival times of vehicles at selected locations and would make control decisions accordingly. If two inspectors were assigned to a route, they would attempt to coordinate with each other so that they would have better overall information. If an emergency occurred, the inspector would need to be at the emergency location in order to effect the proper control actions. This would mean that the inspector would have to drive over to the emergency, conduct any necessary emergency repairs and direct vehicle traffic if necessary.

4.2.3 History of CIS

Toronto's effort which led to CIS began in the 1970's with three main goals: to locate vehicles in real time, to provide a better communications system between central control and operators and inspectors in the field and to improve safety for both passengers and

operators. Their objectives in gathering location information were to improve the operations monitoring and control and passenger information functions. CIS has evolved through six phases over a fifteen year period encompassing different technologies to its present configuration. After each phase, evaluations were performed to determine the success of the phase and whether to continue or discontinue development.

The first three phases of CIS involved defining the requirements for the system, identifying the alternatives, and recommending a system. After these phases were completed in 1974/75, all of the necessary sub-systems were developed sequentially. All of the development of the software and much of the hardware development and training was done in-house. Phase IV, which was completed by the end of 1975, involved testing the system on ten vehicles to make sure that both the technology and the underlying system worked. In Phase V, 100 diesel buses assigned to a single divisional control centre were equipped with CIS. Surveys and measurements of these buses were conducted before and after CIS was installed to determine quantitatively the benefits of the system. Phase V started in 1976 and finished a few years later. Phase VI, which started in 1981 and was completed in 1986, expanded CIS to cover an entire division; the Wilson Garage with 250 buses. A detailed before and after analysis was performed after this phase with the results contained in a June, 1988 report [M.M. Dillon 25].

The entire TTC bus and streetcar system went on-line in 1991 after about a year of hardware and software installation [TTC 63] as part of Phase VII. The main emphasis during the year of installations was to get the basic AVL system installed and on-line by the required deadlines. This meant that some of the other features of CIS that were supposed to be included in Phase VII such as management reporting and passenger information were delayed. Training of controllers and other CIS users was also rushed through. Now that the system has been fully installed, the TTC is starting to implement the management

reporting functions and they are also starting to conduct a cost/benefit analysis of the entire system.

4.2.4 Location Technology

Although the signpost-odometer vehicle location technology used in CIS is not advanced by today's standards, both the communication and computer technologies supporting the location technology are among the most advanced in any transit system. The location technology consists of signposts and odometers. Each signpost transmits its ID signal through the UHF band (at 10.05 GHz) which is received on board the TTC street vehicle. Each vehicle contains two odometers; one tracks continuous mileage and the other is reset every time a signpost is passed. These odometer readings, along with the most recent signpost passed, are transmitted to central control in response to polling on a 20-40 second cycle, which processes them to determine vehicle location. Since an odometer is reset every time the vehicle passes a signpost, controllers receive fairly accurate vehicle locations.

4.2.5 Communications technology

Communications between the vehicles and central control can occur in several ways. At the heart of the communication system is a voice and data link consisting of ten antennas that are distributed across the city such that every route is covered and there is overlap in coverage in case of antenna failure. The operating structure of these antennas is somewhat similar to a cellular network in that any vehicle that is within the sphere of influence of one antenna transmits over that antenna's frequencies. When the vehicle travels out of the sphere of influence of one antenna and into another, the transmission frequency is switched automatically.

Unlike a cellular network, however, each antenna transmits and receives at different frequencies, although when antennas are located at opposite ends of the city, the separation distance is great enough so that the same frequencies can be used. In this configuration, many smaller, less powerful antennas are built instead of one large antenna which may cost more to licence, build and maintain.

These ten antennas control about 25 standard frequencies that the government awarded to the TTC. Each standard frequency has a drift of about 25 kHz and can carry either voice or data communications. Using newer European standards, the TTC has been able to split each standard channel and effectively double the number of frequencies to 45 channels. The TTC has been able to do this by purchasing and developing more precise equipment that reduces radio drift from the North American standard of 25 kHz to the European standard of 12.5 kHz. Most of the channels are reserved for data communications, but some are reserved for voice. The channels are more or less evenly distributed between the antennas. Transmissions occur at about the 400 MHz level, which is a little higher than normal radio transmission frequencies.

Each antenna is responsible for polling the vehicles in its area and for commanding vehicles to switch over to an adjacent antenna's frequencies if the vehicle is about to leave the antenna's sphere of influence. In the polling sequence, the antenna polls all of the vehicles in sequence and requests information on each poll. If no information is forthcoming, the vehicle is polled again 20 seconds later. If no information is received for three or more successive polls of the vehicle, a special channel is opened up which searches for the vehicle in order to get it back onto the communication system.

At every fifth poll in the sequence (i.e. after 4 vehicles are polled), the antenna opens up a general frequency requesting any exception information such as changes in passenger loads, silent alarms or other emergencies. This way, emergencies and other important sig-

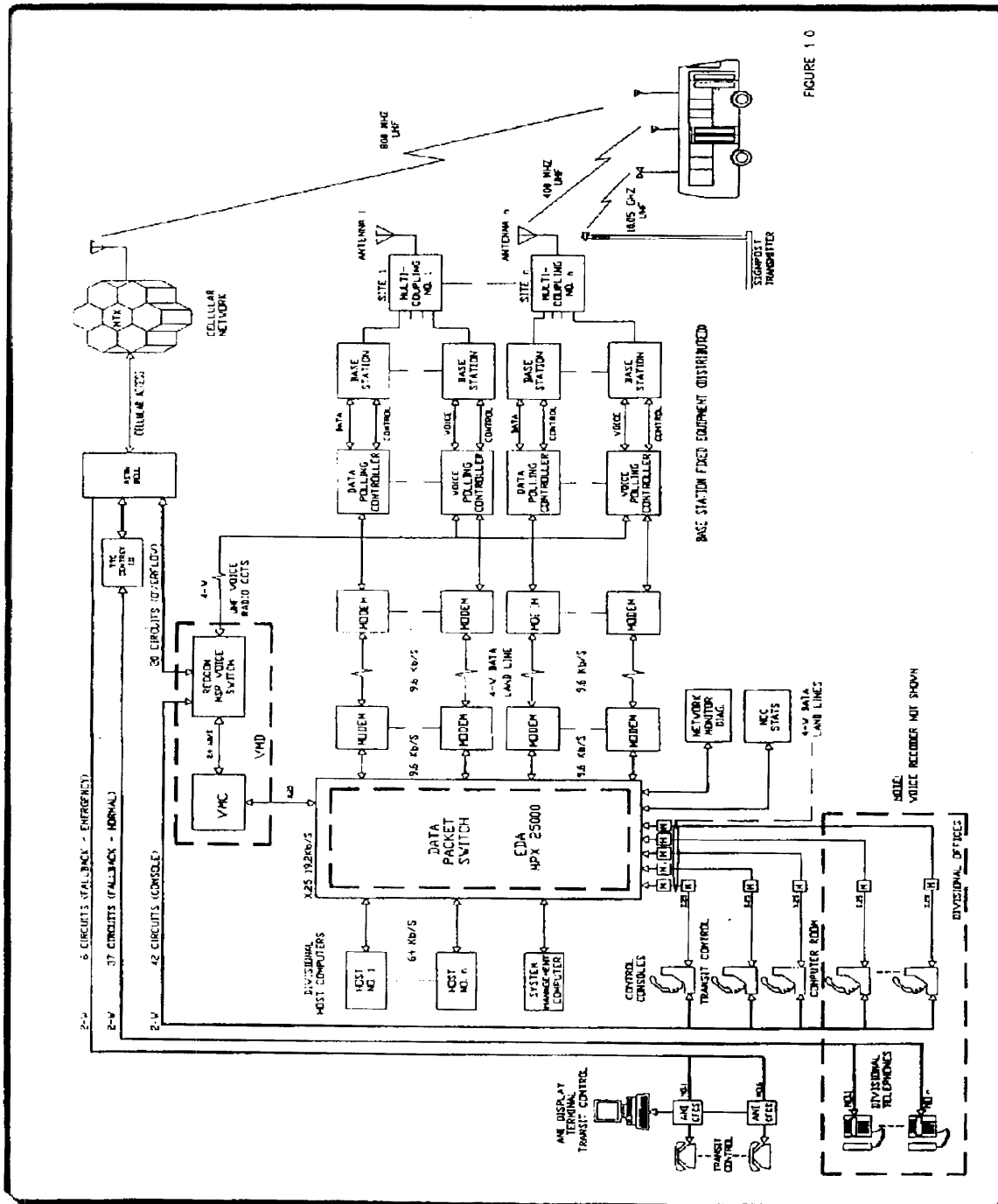
nals are received by central control within 1-2 seconds instead of the normal 20 second polling interval. Channel switches, polling, and message routings are all controlled by data or voice polling controllers. This information is routed through the controllers into central control and eventually down to the division control centers.

Should the primary voice-data network fail, the system is linked to a backup cellular voice network operating in the 800 MHz range that is a shared common public network. Each TTC vehicle has a unique cellular telephone number assigned to it and in case all voice channels on the primary network are occupied, controllers can automatically switch to the cellular network. Like public users, however, the TTC must pay for each minute of cellular time, but the voice communication is a lot clearer than the primary network and the vehicle can communicate anywhere in the world where a cellular network is set up. Operations control can still be conducted during failures and times of heavy use by using the cellular network, but only voice messages can be transmitted through this network. A schematic of this system is shown in Figure 4.1.

4.2.6 Computer Hardware and Software

The CIS system has a complex computer system overseeing, integrating and controlling its operations. On the vehicle, the main equipment is the Transit Universal Micro Processor - nicknamed TRUMP, which controls all of the data that the vehicle transmits and receives. The TRUMP contains a UHF digital radio, a cellular telephone, microphone, display screen and keypad. Receivers on top of the vehicles and sensors connected to the odometers receive the information necessary to perform vehicle location [TTC 24].

Figure 4.1: Schematic of CIS¹



1. Source: CIS: APTA Conference [24]

With the assistance of the TRUMP unit, the operator can receive text and voice messages from controllers. The unit also displays schedule adherence information (downloaded from the central computers) in the form of minutes behind or ahead of schedule. The operator can also send information to the inspectors such as passenger loads, emergency alarms, silent alarms, occurrences of fare disputes and simple yes or no answers to text based questions. Automatically, the TRUMP unit sends location data, the status of the vehicle's engines and the status of the vehicle's doors every polling cycle.

A microphone and loudspeaker are also connected to the TRUMP unit. The microphone can be used by controllers to listen to conversations occurring on the vehicle and is useful in cases of on-vehicle emergencies. The speaker is used by either the operator or controller to relay messages to the passengers on board the vehicle and is also very useful in cases of fare disputes (this allows for disputes to be handled by the controller, taking the burden of dispute resolution out of the hands of the operator) and in providing information, such as on service disruptions, directly to passengers.

Service is controlled from ten operation control centers with each center controlling all the vehicles associated with its garage/district. Each controller is seated at a workstation which consists of three monitors, an IBM PC 386/50 computer, a CIS handset, a keyboard and a dual voice/data telephone that patches into the central control computer and can send voice or text messages to vehicles.

Two monitors are devoted to showing graphics of the individual routes with each routes shown as an "oval" with the long sides corresponding to each direction of travel, although they do not correspond to the actual physical geography of the route. On one side of the line, the scheduled location of the vehicle is shown (downloaded from the planning department), with the actual location shown on the other side. Depending upon the disparity between scheduled and actual position, inspectors can see how far off schedule any

vehicle on a route is. Controllers can also see gaps in service through this graphic. The two monitors together can show up to 6 routes, thus it is possible for an inspector to monitor and control up to 6 routes simultaneously.

The third monitor is an emergency/statistics screen with the top portion showing every vehicle's deviation from schedule in minutes and "pathological" vehicles (i.e. vehicles that are being tracked that have not logged into the system, vehicles that are far ahead of or behind schedule, vehicles that have pressed a red or yellow alarm). The middle part of the screen shows detailed statistics for any vehicle selected by the controller including odometer readings, engine status, door status, the run number and ID of the vehicle, the operator ID, and the signposts that the vehicle is between. Inspectors can send text or voice based messages over the voice-data line or can send voice-based messages over the cellular network.

The control center software is intended to handle short turns, expressing and emergency re-routing although currently it only handles short turns reliably. Since the system uses signpost-odometer technology, the software has to be sophisticated enough to track vehicles when they go off-route by reintroducing the vehicles back into the system at the right points.

Although each division control center is intended to handle only the vehicles within the division, it is possible to control any vehicle at any division. This is particularly useful for evening and overnight operations, where fewer vehicles are operating system-wide. The TTC has a policy of shutting down some control centers early and transferring control to other control centers. In the extreme, for night service, only two division control centers (Roncesvalles in the west end and Malvern in the east end) are needed to control system-wide service for all 10 divisions.

The control centers' workstations and the TRUMP units on the vehicles are all tied together through a central server which is essentially the "brains" of the system and processes most of the information that flows between the operators and the controllers. The "server" consists of fifteen networked IBM RT super-micro computers, each assigned to handle one division and one special super-micro assigned to coordinate the other servers. If one server goes down, the system offers redundancy and spare capacity so that another server can take its place.

The servers initially receive information from either the TRUMP units or the control center workstations. After determining the final destination of the information, the servers process the information and relay it to the correct channels. When a message comes in from a vehicle, the server ascertains its destination, determines its ID, performs the necessary calculations and then forwards the results to the correct control centre. A similar procedure working in reverse occurs when the controller sends a message to the vehicle. Examples of processing done by the central server are the calculation of positions, the calculation of deviations, and the accommodation of requests from operators and inspectors.

All of the CIS programming is in a standard language (Microsoft C) and all of the machines run on a standard operating system (Unix). Use of standardized languages and operating systems makes the transfer and upgrading of software to different systems easier than if the software were developed using customized languages or operating systems.

When a vehicle enters revenue service, the operator logs into the system by inputting the badge ID, the run number and the route number of the vehicle. TRUMP automatically sends this information to the controller and it is displayed on their screen at the fifth poll interval. Every 20 seconds or so thereafter, the polling controller sends out a signal to the vehicle without waiting for either a prompt or an acknowledgment. The response signal from the TRUMP contains information on the position of the vehicle based on the last

signpost passed and the odometer reading since then. The signal also contains information on engine status, door status, the operator ID, the vehicle run, the vehicle number and the last signpost the vehicle has passed.

All that the signpost does is send out a signal bearing its ID. A receiver on the vehicle picks up the ID, then the TRUMP unit sends this ID along with all the other information to the control centre and also resets the odometer. When an emergency occurs, the operator presses an exception key and the signal is sent to the control centre as the response of the nearest fifth poll. The operator can also make use of exceptions to report passenger loads, fare disputes, answer text questions or initiate voice communications. The operator and controllers can communicate in three ways. One is through the TRUMP unit through text messages sent through one of the UHF channels, the second way is by voice through the microphone and the third is by cellular telephone. Both the operator and the controllers have the ability to initiate conversations. The text messages responses sent to the inspectors at the control centre through the TRUMP are limited to yes or no answers. The operator logs off the vehicle at the end of the run.

4.2.7 Human Factors

With much of the discussion to date focusing on the technological aspects of the CIS system, it is easy to lose sight of the fact that for CIS to be effective it must help its end users. It is intended to make all of their jobs more efficient and easier to perform.

CIS has caused an evolution in the roles that these individuals play. Operators, in addition to driving the vehicles, are now responsible for making sure that their vehicles are initially logged onto the AVL system. More local monitoring and more control responsibilities are passed on to them through the TRUMP units which inform them of their schedule adherence. They also act as secondary community watchers. Inspectors

who previously worked exclusively in the field are now commonly rotated between the control rooms and the field. Inspectors in the field are now primarily responsible for responding to emergencies and dealing with the public under both normal and emergency conditions.

The controllers in the control room have much more information to assimilate and deal with. Before CIS, they would receive only occasional updates from inspectors and operators. With CIS, they receive location information on a system-wide basis along with schedule adherence and other pertinent information about every vehicle in the system. Controllers are getting a much better picture of their routes in general, and there is some anecdotal evidence that this is leading to better control decisions. The position has become more stressful, however, as inspectors now have more information to deal with when they make decisions.

Passengers do not notice many physical differences in the CIS equipped vehicles, although they may notice improvements, when emergencies occur, in the form of quicker response times and better mitigation measures. Passengers may also notice better service in terms of headway regularity or on-time performance as evidenced by a decrease in complaints and an increase in commendations.

4.2.8 Off-line Functions

CIS includes several types of management reports which, when operational, will be able to provide summaries on operations for any vehicle on any route at any time. The reports developed to date include [Levinson 40]:

- Period Summary Reports
- Route Reports
- Running Time Reports
- Point Reports
- Layover Reports

- Schedule Adherence Reports
- Route Operations Reports
- Segment Schedule Adherence Reports
- Lost Mileage Reports
- Change-Off Reports
- Key Push Reports

Presently, the reports are being generated manually, but in the future, these reports should be automatically generated. Currently, most of the AVL information is physically stored in raw form on magnetic disks. There is currently no system available automatically to compile, summarize and transfer this data to analysts. Access to this data is also limited to when a passenger complains about a particular route. When this happens, the portion of the data that includes the route and time of the complaint is retrieved, compiled and analyzed in order to respond more effectively.

When these reports become fully integrated into the system, they will provide decision-makers with a wealth of information on operations so that they can make more effective operations planning decisions. This information can also be used to judge the effectiveness of CIS in general and of individual control decisions specifically. When integrated with an Automated Passenger Counter (APC) system, CIS might also be able to automate its data summarization process much like OC Transpo has done with their APC system.

In addition to generating these static reports, the TTC is also developing a dynamic reporting system that can display information that is specific to a manager's needs. In a static reporting system, the TTC is faced with the challenge of organizing a very large database and determining the data that is most important to managers. Every day, about 2 megabytes of information is collected by CIS for each division, thus it is easy to get overwhelmed with data, and TTC wants an effective way to filter out needed information.

In its proposed dynamic reporting scheme, the TTC would use off-the-shelf software that is specifically designed to provide a user-friendly interface for shared databases. These programs enable managers to take data from a shared central database and display it in easily comprehensible ways, such as in tabular or chart format. These programs also enable quick statistical analyses and database queries to provide further information on a subset of the data. For example, a manager could request the summary statistics for an entire division, then zoom in on one route of the division, and if desired, to one vehicle on the route. In this dynamic reporting scheme, the manager is able to generate the statistics and summaries he or she wants and is not constrained to pre-defined reports.

4.2.9 Development and Installation of CIS and Training of Users

The CIS system has resulted from a long development process that is still continuing. Generally, CIS's development is viewed as being successful, all the systems and sub-systems work reliably and there have been smooth transitions between phases. Part of the reason for this success was the continuous assessment of CIS as it was being developed. After Phase V and Phase VI, cost/benefit analyses were conducted to determine whether or not to proceed with the next phase. Opinions are solicited from all users of CIS to help determine hardware defects, software bugs and user incompatibilities, and a team at the CIS control centre works full time to address all problems. Thus, the system is continually improved although recent staff cutbacks have slowed this process.

The installation process has also largely been a success. Phase VI was installed and operational with a minimum of problems and CIS was successfully installed on all vehicles and at all divisions in less than twelve months, between 1990 and 1991 (one of the objectives of Phase VII). This feat has been accomplished, however, at a priced in reduced functionality. In the original development plans, Phase VII was supposed to include man-

agement reporting, passenger information and passenger counting devices, but as of April, 1994, none of these systems has been installed. Past tests have found the current technologies used for passenger counting to be unreliable which is one of the reasons why they have not been yet implemented. Management reporting and passenger information have not been implemented because of time and resource constraints. The developers of CIS were primarily interested in getting the real-time functions and the overall system on-line before focusing on the off-line reporting and passenger information.

Development in the earlier phases also had trouble keeping on schedule. Phase VI, which was to have taken three years to complete actually took about four because of software development, staffing and computer capacity problems [TTC 26]. This is one of the risks of a truly in-house developmental process for new technology.

The training process has not been entirely successful either. The controllers who use CIS usually come from the field inspector ranks and they are initially trained in the control room for a three week period. After the training period, these controllers are usually sent back out in the field to perform the duties they were doing before their training. Sometime later, this controller will be assigned back to the control room where he or she will be expected to use the CIS system. The strategy is that with this method, controllers will be able to use the knowledge of geography and street conditions gained out in the field back in the control room. The strategy however can result in controllers forgetting much of their earlier training because of the time away from CIS and being forced to learn the system “on the fly” by experimenting with the CIS functions and by learning from other controllers.

4.2.10 Costs

It is often difficult to obtain reliable cost data for AVL systems. Sometimes, agencies report overall costs of implementations, but do not release detailed costs for individual components. There are also many issues that have to be dealt with when determining cost such as deciding whether a subsystem should be included in the overall costs, or whether it is actually a required part of another system. If this subsystem is part of both parent systems, then cost allocation becomes an issue.

Also, some costs, such as in-house labor for development, are hard to track accurately. Sometimes, programmers and other personnel would be pulled off other duties (e.g. subway operations, data analysis) to work on CIS. One of the managers interviewed at the TTC stated that some of these costs, which are hard to determine because sometimes they didn't distinguish CIS related work with other work, may not have been included in the overall costs. As a result of these potential errors, the CIS costs that are presented below should only be viewed as estimates of the true costs.

The CIS Phase VI final report [26] summarized the entire project costs for Phase VI compared to original estimates, as shown in Table 4.1 (all costs are in US dollars). These cost estimates tell us a few things about CIS and perhaps about AVL systems in general. First, costs may be hard to predict. In this case, projected and actual costs differed by only 10%, but this masked the fact that some costs were greatly underestimated and others were overestimated. Second, since these are relatively new technologies being implemented, development may not proceed perfectly as planned. In this example, the TTC was unable to obtain the required frequencies and passenger counters were not accurate enough for the TTC's needs.

	Original Project Budget	Estimated Final Costs
Purchase of Vehicle Equipment ^a	\$790,000	\$835,000
Purchase of Console Equipment ^b	53,000	53,000
Wiring of Vehicles by Equipment Department	144,000	144,000
Software Development by Management Services Department & Consultants	284,000	630,000
Engineering and Installation by Plant Department	292,000	410,000
Retrofit of existing CIS Phase V Equipment to New Frequencies ^c	29,000	--
Passenger Counters ^d	102,000	--
Other Equipment Purchases ^e	343,000	245,000
Total Estimated Project Cost	\$2,040,000	\$2,260,000

Table 4.1: Original Projected and Estimated Total Costs of CIS Phase VI^f

a. The vehicle equipment costs are the total payments made to RMS Industrial Controls Inc. for the supply of TRUMP units and all peripheral equipment on vehicles, including microwave receivers, odometer sensors, P.A. speakers, engine and door sensors, microphones, junction plates.

b. The console equipment purchase includes three "full" (three-screen) consoles plus the single-screen "mini"console.

c. Due to delays in receiving Federal approval for new radio frequencies, which could accommodate Metro-wide CIS, it was necessary to have Phase VI equipment built to operate on Phase V frequencies. At some time in the future, it will be necessary to retrofit all of the CIS equipment to new radio frequencies. (Reference Commission report dated July 21, 1981.)

d. A study of passenger counters has been completed under a separate project funded by the Ministry of Transportation and Communications. Since a suitable final system configuration was not proven at the time of vehicular equipment installation, it was decided to delete the installation of passenger counters from Phase VI. (Reference Commission report dated September 28, 1982.)

e. "Other Equipment Purchases" includes all other acquisitions related to Phase VI of CIS including additional radio base stations, signposts, mini-computer components, etc.

f. All costs are in Canadian dollars

Phase VI installation included 262 buses, which gives a per bus cost of approximately \$8,600. This cost does not include, however, the costs of previous phases of development, which increases the total cost to about \$4 million or a per bus cost of about \$15,000.

Going back to the table, strictly vehicle-related costs turn out to be approximately \$1.34 million or almost 60% of the total costs. These costs, which vary directly with the number of vehicles includes purchasing, wiring and installing vehicle equipment (it is assumed here that the vehicle portion of the installation costs is about \$370,000 of the total

\$410,000 cost). The hardware costs for central control and the communications network are approximately \$340,000 or only 15% of the total costs. Software costs make up the remaining 25% of the total cost.

These are the approximate costs for a centralized control system with limited decentralized functions. It would seem likely that a more decentralized system would have the vehicle bearing a larger proportion of the costs. The observation to note here, however, is the fact that central control facilities are not a major determinant of cost for a large system such as Toronto's. For the benefits that centralized monitoring and control can give you, this example gives some support to the view that centralized control may be more cost-effective than decentralized control.

On a system-wide basis, the full scale implementation of CIS was estimated to be about \$27.3 million or an annualized cost of \$2.6 million [59]. Annual operating costs are estimated to be around \$1.6 million for an overall cost of \$4.2 million annually. These costs include installations on:

- 2000 buses of varying types and 300 streetcars
- 10 divisional control centres, 9 of them for buses and 1 for streetcars
- 1 CIS control centre linking the divisional control centres

This cost also includes all prior research and development costs conducted in the previous phases of CIS. On a per vehicle basis, the cost turns out to be about \$12,000 per vehicle. One manager estimated the cost of the TRUMP unit on vehicles alone to be about \$7,300 per vehicle, thus it is clear that the on-board vehicle costs make up a major portion of the total costs. With such a large operating fleet to contend with, it seems likely that the controlling element in total cost is the equipment that has to be installed in each vehicle rather than central control facilities.

4.2.11 Benefits and Effectiveness of CIS

A cost/benefit study released in June, 1988 [25] evaluated Phase VI of CIS and then estimated systemwide benefits and costs. A critical evaluation of this analysis is provided next.

From a study of passenger boardings, ridership, schedule adherence and manpower utilization for the routes controlled by Wilson garage, the report estimated the following financial benefits of CIS:

1. 1% savings in vehicles and manpower at Wilson garage. As a result of this, the report projected a 2-3% savings systemwide, amounting to annual savings in capital and operating costs of between \$4.3 and \$6 million.
2. \$1.3 to \$2.6 million increase in passenger revenue systemwide based upon ridership increases at Wilson.
3. increased productivity of supervisory staff could see as much as 27 inspectors either being assigned to other duties or being used more effectively in the field. A cost of \$1.0 million would otherwise be incurred if these staff were hired exclusively for street supervision.
4. an annual savings of \$370,000 due to a reduction or reassignment of data collection field staff when APC's become integrated into CIS
5. greater number of road calls and increases in change offs resulting in additional operating costs of at least \$460,000 a year.

The largest items were the cost savings associated with projected vehicle and manpower reductions and the revenue impacts associated with ridership gains, producing an estimated annual benefit of between \$6.6 and \$9.5 million. This was compared with the annualized cost of CIS of \$4.2 million to come up with a cost/benefit ratio of from 1.6 to 2.2. On the face of it, this makes a good case for the value CIS, but it is important to note here that these benefits are only projected benefits and have not yet been fully realized. Also, a closer look at some of the analysis raises some questions about the results.

On the issue of vehicle and manpower savings, the report measured Daily Passengers Per A.M. Peak Period bus from 1981 to 1987 at all 10 garages and compared the CIS equipped garage (Wilson) with all the other garages. The report suggests that the more passengers carried on an A.M. Peak Period bus, the more efficiently vehicles are being utilized. This would translate into a reduced need for buses and thus a cost savings. The report found an 0.8% improvement in this statistic at Wilson (from 976 to 985) at the same time the rest of the system suffered a 1.2% decrease (from 1029 to 1017). Based upon this and the fact that management reports and passenger counters were not used at Wilson, the report made a “conservative” estimate of a 2-3% system-wide savings in terms of required fleet size.

First, it is not obvious that Daily Passengers Per A.M. bus is a good indicator of vehicle utilization and hence required fleet size. A more appropriate measure might simply be the differences in buses required before and after AVL implementation after factoring for route and schedule changes. Even if this measure is used, it indicates that utilization at Wilson is below system average to begin with and then improves, but is still below system average utilization. This indicated that there was slack in Wilson, and the gains may just have resulted from tightening up the slack rather than from CIS per se. A stronger case for CIS would have been made if vehicle utilization had improved so that Wilson out-performed the system average, thus the gains could be better attributed to CIS.

In addition, by comparing Wilson with the rest of the system in order to isolate CIS effects, the analysis implicitly assumes that external influences are the same for Wilson as for the rest of the system. Over the analysis period however, congestion in the Wilson area increased relative to the rest of Toronto. In addition, population and employment dramatically increased in the City of Vaughan, which is just north of Wilson. These two effects seem to indicate that external factors affecting Wilson were quite different than those

affecting the rest of the system, thus the assumption appears to be questionable. A possible way to isolate CIS effects more effectively would be to conduct comparisons between similar routes in the same garage rather than between garages if possible.

The TTC did conduct comparisons of vehicle usage from January 1982 to July 1983 at Wilson [26]. During this time period, CIS was installed on several selected routes at Wilson, thus since the routes were in the same geographic area and no major service changes occurred during the period, the effects of CIS were better isolated. The vehicle requirement for CIS-equipped routes decreased by 11.5% while the vehicle requirements for non-CIS routes decreased by only 2.3%, thus it was concluded that CIS had a net effect of reducing vehicle requirements of 9.2%. While this analysis isolates the effects of CIS more effectively, it assumes that all routes in the area are similar, which is an oversimplification.

In terms of ridership, the report estimated a ridership growth of 0.5 to 1% based upon ridership growth at Wilson compared to the other divisions. Their measure of ridership growth is percentage change in passengers/mile. Although this is a good measure to judge productivity, it is not a true measure for ridership since this measure can increase either due to an increase in passengers or a decrease in service. Other measures such as passengers and passenger-miles are better measures of ridership. These measures, however, do not effectively isolate CIS effects if they are only compared on a systemwide basis. From this analysis of passengers/mile and the previous one depicting Daily Passengers Per A.M. Peak Bus, although general productivity has increased, it is still not clear whether this increase came as a result of increased ridership, decreased vehicle usage or both.

The report did provide some concrete evidence of service quality improvements from an analysis of schedule adherence. Means and standard deviations of headways and standard deviations were calculated for a Jane Street route at different time periods before and

after CIS was implemented. The results shown in Table 4.2. indicate that schedule adher-

Time Period	Observed Headway					
	1982		1984		1987	
	Mean Headway	Standard Deviation	Mean Headway	Standard Deviation	Mean Headway	Standard Deviation
11 A.M. - 2 P.M.	6.22'	4.14'	6.79'	3.23'	5.97'	3.62'
2 P.M. - 4 P.M.	3.58'	4.14'	3.89'	3.45'	3.33'	2.73'
4 P.M. - 6:30 P.M.	2.10'	2.08'	2.62'	2.85'	2.92'	2.91'

Table 4.2: Schedule Adherence: Jane Bus Route^a

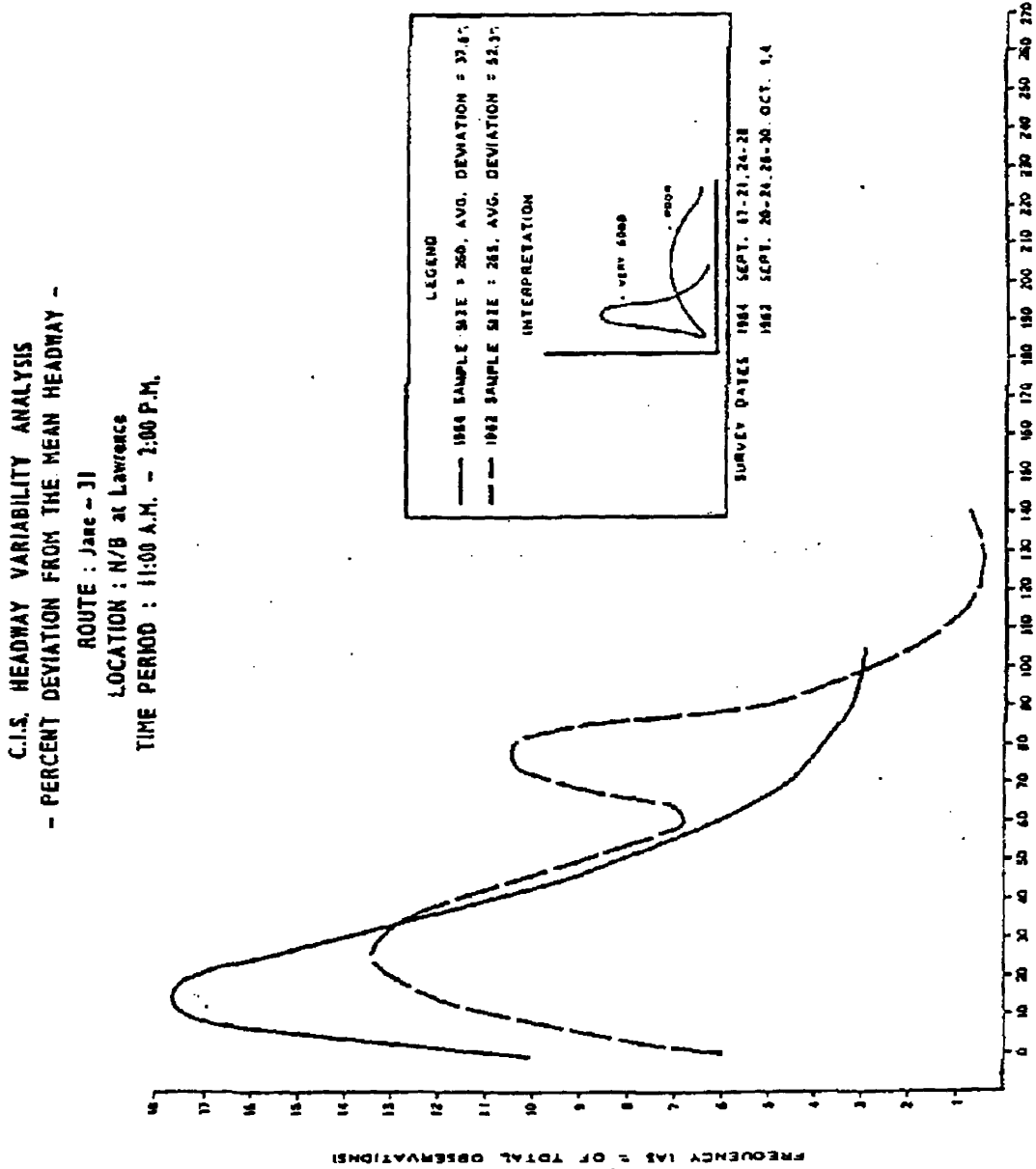
a. Source: TTC Planning Department

ence generally improved except in the P.M. peak period, which was affected by increasing traffic congestion from 1982 - 1987. In addition to measuring schedule adherence by determining means and standard deviations of headways, the TTC graphed a frequency distribution of headway variation, which was defined as percent deviation from mean headway. An example of this graph is shown in Figure 4.2.

The last measure reported was reaction from passengers in terms of passenger complaints. Within Wilson, the number of complaints per passenger decreased by 17% from one complaint every 1427 passengers to one complaint in 1714 in terms of punctuality, and decreased by 50% (from 1 in 2199 to 1 in 4433 in terms of fare or transfer disputes. When compared with the systemwide averages, Wilson had 24% and 19% lower complaint rates respectively on these two measures.¹

1. Calculations from Table 7 of M.M. Dillon [25]

Figure 4.2: Percent Deviation From Mean Headways



Within the TTC, passenger complaints are used as a proxy for schedule adherence, since there is believed to be a high negative correlation between service quality and number of complaints. The report points out that the number of passenger complaints has

decreased since CIS came on line suggesting that service reliability has improved. The study reported that many users of the system also believe that CIS has made them more effective. Controllers believe that they are making better decisions and operators believed that they are more successful at adhering to schedules.

One of the reported benefits is the potential savings that can be achieved by assigning some supervisory staff to other activities. The TTC evaluation was conducted by comparing vehicle to supervisor ratios at Wilson with the full system. By normalizing with respect to the number of vehicles, total supervisory requirements reflecting such things as route or schedule changes can be accounted for. Table 4.3 from the evaluation report charts supervisory needs from 1983 to 1988. This table shows that over the 5 year period, supervisors have become more productive system-wide but both the productivity and its increase was highest at Wilson where CIS was installed. This increased productivity translates into a 2 bus/supervisor increase in efficiency which the evaluation translated to a savings of 27 inspectors system-wide.

	1983	1984	1985	1986	1987	1988	% increase 1983-1988
Supervisory Staff ^a	153	153	155	155	155	157	2.6
A.M. Peak Vehicles	1578	1615	1641	1668	1704	1730	10.0
Peak Veh./Inspector	10.31	10.56	10.59	10.76	10.99	11.02	6.9
A.M. Peak Veh. (Wilson)	226	241	250	258	261	267	18.1
Inspectors (Wilson)	20	20	20	20	20	20	-
Peak Veh./Inspector (Wilson)	11.30	12.05	12.50	12.90	13.05	13.35	18.1
Source: TTC Transportation Department							

Table 4.3: Surface Supervisory Staff

a. Includes Wilson Division

Even if these savings could be realized, they have not been since the TTC has followed a policy of reassigning supervisory staff rather than reducing their ranks. The agency feels that supervisors need to be retained in order to improve passenger relations, to respond to emergencies and to improve service in general.

A 1991 Supervisory Assignment Report [65] shows the effect of this policy. From 1988 to 1991, total supervisory staff actually increased from 186.5 to 287.5 during the period in which CIS was installed system-wide. Also Duerr and Wilson [31] estimated an operator/supervisor ratio for the TTC bus system in 1991 to be about 19.3. If a 1.5 operator/bus ratio is assumed, then the bus/supervisor ratio would be 12.9, which is about a 17% efficiency increase from 1988. This means that although supervisory efficiency increased system-wide as a result of CIS, supervisory positions increased as well. This suggests that the benefits of CIS from a supervisory perspective should be measured in terms of service quality rather than cost savings.

In addition to quantifiable benefits, the June 1988 report listed some non-quantifiable benefits of CIS including:

- Improved emergency response times
- Improved restoration of service
- Improved passenger relations
- Creation of incident reports
- Potential for real-time passenger information
- Community safety and security

4.2.12 Opinions about CIS

From interviews with TTC staff combined with interviews made in the June 1988 evaluation report, the following opinions about the impacts of CIS from managers, operators and inspectors have been gathered.

Managers

Managers like the system a lot. They were the ones who originally pushed for CIS to be developed and touted the potential benefits of the systems. Even now, with shrinking budgets and with some delays in implementing the full system design, they still fully support CIS. Unfortunately, with the economic recession still affecting the area, the commission has less funding to improve the system. Managers say that they are slowly moving towards a more automated system of reporting, which is of special interest to them. The managers also strongly believe that customers are receiving better service as a result of CIS, pointing mainly to the decrease in passenger complaints, and their personal experiences. No real statistical analyses have been conducted to yet quantify effectiveness, however.

Managers recognize that CIS will not solve all their problems and the human role will remain paramount. In their movement towards improved service, they see the need for continued interaction with the public through operators and through inspectors on the street which was the agency's main motivation behind retaining supervisory staff.

Inspectors/Controllers

Inspectors have mixed opinions about CIS, but in general they support it. They agree with the managerial point of view that the human element will always be a big part of CIS and they believe that users are well integrated into CIS. Manual inputs are essential since good monitoring and control comes from experience working in the field. Many inspectors feel that you don't become an effective controller in the control room without spending time in the field.

You need to understand the geography of the system, individual operator needs and capabilities, and most of all, you need experience in the field to determine which controls will work where and which controls won't. None of these elements can be programmed

into CIS, but they can work alongside CIS to achieve the proper goal. Like managers, they view CIS as a very useful tool, but as with any tool, it can be used effectively or ineffectively, and the better inspectors will always make the better decisions regardless of the level of help provided by any system.

Many of the faults that they find with CIS are software related, although some problems are hardware related. The problems come primarily as a result of the limitations of the signpost-odometer location technology. As long as a vehicle stays on the route, there is no problem with locating that vehicle. However, when a vehicle is subject to a control action, problems may occur with CIS misjudging the vehicle's location. One example is when a vehicle is diverted off a route right after passing a signpost, CIS will assume that the vehicle is still proceeding along the normal route as planned unless locations are specifically changed by the controller. This error will be corrected only when the vehicle passes another signpost: until then, CIS will incorrectly assume that the vehicle is still moving in the same direction along the route.

Another problem occurs if the diversion called for a change in direction. When the vehicle comes back on route after the diversion, CIS will believe that the vehicle is still going in the previous direction unless the controller physically adjusts the vehicle to its proper direction. Sometimes, this may not happen because the controllers are preoccupied with other matters. Sometimes it can take up to 30 minutes before a vehicle can again be located properly. The software can handle short turns most of the time but has trouble with this function occasionally. Many times, controllers have to reset vehicle locations manually after diversions.

Although this is essentially a limitation of the location technology, the controllers point out that software can be programmed to deal with this condition more effectively than at present. Controllers would like to be able to input details of the diversion into CIS

so the system can properly anticipate the vehicle's movements and minimize the errors. It must be recognized however that signpost-odometers will always lack the advantages of absolute location that a more advanced technology such as GPS would provide. The controllers also point to other software weaknesses such as interfaces that aren't very user friendly and the lack of control options that are available to them.

In terms of hardware, the controllers point out that sometimes the communications systems are not highly reliable. For example, on occasion it may take 5 or 6 attempts before a communication gets through and is acknowledged. They admit that sometimes controllers ignore messages from operators and vice versa, but they say that a lot of this miscommunication is due to interference and capacity problems. The controllers note that they are probably communicating with the operators more often than intended in the design of CIS.

One benefit that CIS was intended to provide was the reduction of voice communication and its conversion to data which takes up less bandwidth. Both controllers and operators like to communicate frequently using both forms however, with operators preferring voice interaction with controllers and controllers preferring to receive voice acknowledgments of their control instructions. Controllers feel that with better training of both controllers and operators, the system can be utilized more efficiently.

The inspectors generally agreed that they are able to make better decisions with CIS because they can now see the entire system instead of just one point. They point out, however, that their jobs have also become more stressful: with more information comes more options and greater responsibility. Before, a controller only had to make one control decision every few minutes and had more "down time" when nothing important was happening. Now, with all the extra information coming in, they have to make more decisions and assimilate more information to make these decisions. Interestingly, while in the streetcar

depot, the inspectors felt that they made more control decisions than before, on the bus routes, they believed that they intervened less frequently as a result of CIS.

The inspectors believed that in some situations, better control decisions can be made out in the field as opposed to a CIS control room because the street inspectors have better information on the local situation. In one tale, an inspector in the control room decided to divert streetcars upstream of an accident point. What he didn't know was that the accident had been cleared up by the time the decision was made and thus needless diversions occurred. If the inspector was in the field, he would have known that the accident was about to be cleared up and would have made the proper decision of waiting instead of diverting. This example serves to remind one that AVL systems can not be the sole basis for some decision-making.

When asked about their opinions of their changing working environments, inspectors were generally indifferent in their choice between working in the field and working in the control room with each having advantages and disadvantages. Although they are sheltered from the elements in the control room, many inspectors feel that they lose their human touch when they lose their interaction with the public and the operators and are forced into a common room.

Operators

Initially, the unions representing the operators and inspectors were opposed to the development of the CIS system because they saw it as an attempt to cut back labor through automation. The operators were skeptical of CIS for the same reason as well as being concerned about the idea of big brother watching their every move and possibly penalizing them for running off schedule for even a minute. Their opinions, however, have changed. Until recently, no labor reductions have occurred and the reasons for recent cutbacks were not CIS-related. Both the unions and operators now feel that CIS provides a better and

safer environment when they are driving their vehicles, thus operators feel more secure. All they have to do is push a button for emergencies or fare disputes and outside authorities can handle it without the need for active participation from the operator. Some operators will even refuse to drive if the CIS system is not working.

Managers feel that operators have also adopted the commission's objective of better service. Operators want to be on time and feel that CIS helps them achieve that goal. Some operators, however, have not fully accepted CIS, preferring traditional methods and feeling that they can do their jobs just as well without active surveillance. Nor do they like the extra requirements that CIS imposes on them, such as logging in and the constant need to monitor the console. There are still some misconceptions by operators about the capabilities and actual uses of CIS.

Operators do feel that CIS helps improve the consistency of their duties and balance the workload between operators so that they end their duties on time, thereby getting home promptly.

4.2.13 Overall Evaluation

Back in the 1970's when developers envisioned the role of CIS, they imagined a system that would help the TTC maintain and even improve service in the face of growing ridership and increased congestion. They saw a system that would be developed slowly over time and would integrate well into the user environment. For the most part, this has been the case, but like many other systems of this type which were touted to bring a multitude of benefits and cost savings, there is still incomplete evidence that CIS has achieved all of its goals. The strength of CIS's development and ongoing improvement process, however, puts it well on its way towards achieving these goals in the future.

CIS went through a largely successful extended development and installation process. Since CIS was gradually phased into normal everyday operations over a period of over 20 years, many problems and deficiencies were worked out before full-scale implementation took place. The TTC also took pains to make sure that the CIS project was going in the right direction in terms of technologies and functionality before proceeding onto the next phase of development. Personnel were given time to integrate themselves into the system and a feedback loop was created between the users and the developers in an ongoing process to solve problems within CIS and to suggest improvements.

Parts of this process were rushed or short-cut, however, in the final push for system-wide implementation, notably staff training, some software development, management reporting and passenger information. Some software and hardware-related problems still exist, operators and controllers are communicating with each other more than expected causing congestion over the communications system and operators and controllers are not regularly providing inputs (like passenger loads) that could make the system more effective.

The result is that in its current stage, CIS has not yet achieved its full potential. Users need to be better trained in the proper use of CIS, probably entailing more formal training sessions including optimization of control room procedures to minimize unnecessary communications. These problems are relatively small ones, however, and must be anticipated as growing pains in implementing any large scale system. The philosophy behind the CIS system and its development appears to enable it eventually to achieve its full potential.

The question then to be asked is, "What is the full potential of CIS?". Previous studies like the June 1988 report and the final report on Phase VI do not provide all the answers to the potential benefits and cost savings. To give these implied impacts greater credibility,

better data needs to be collected and analysis methods need to be more rigorous. Interviews from the TTC staff and preliminary results from the study seem to indicate that significant potential net benefits do exist. It does appear that at least in terms of real-time and off-line impacts, the true potential exists more on the service improvement side than in reductions in operating costs. If it is, then perhaps it is better to focus evaluation on measures of service improvements rather than on cost savings.

Even if cost savings are taken out of the picture, the other benefits of CIS are impressive. CIS is very successful in improving safety and reliability. In a municipality where crime is on the increase, CIS provides a level of safety that is welcome. Even if the added benefit of having an operator press a silent alarm or register a fare dispute is only slightly better than having the operator phone in the emergency on the radio, the psychological security that CIS provides to the operators and passengers is a very important benefit. CIS also reduces response time and allows faster restoration of services. Anecdotal evidence and limited schedule adherence results also suggest that CIS is helping to make service more reliable.

4.3 OC Transpo

4.3.1 Introduction

OC Transpo is responsible for the operation of approximately 800 buses in the Ottawa-Carleton region. This system is strongly radial in form, with many of the routes using an exclusive busway system that goes right to the heart of the central business district. Like Toronto, OC Transpo began thinking of ways to apply technology to their bus system as early as the 1970's but pursuing quite different goals and objectives. Instead of using technology to optimize their day-to-day operations in a large-scale manner, OC Transpo

decided to implement technology incrementally to aid in relatively specialized functions. To this end, they developed smaller, specialized systems. Most of their applications of technology were for functions that operated off-line, but some operated in real-time.

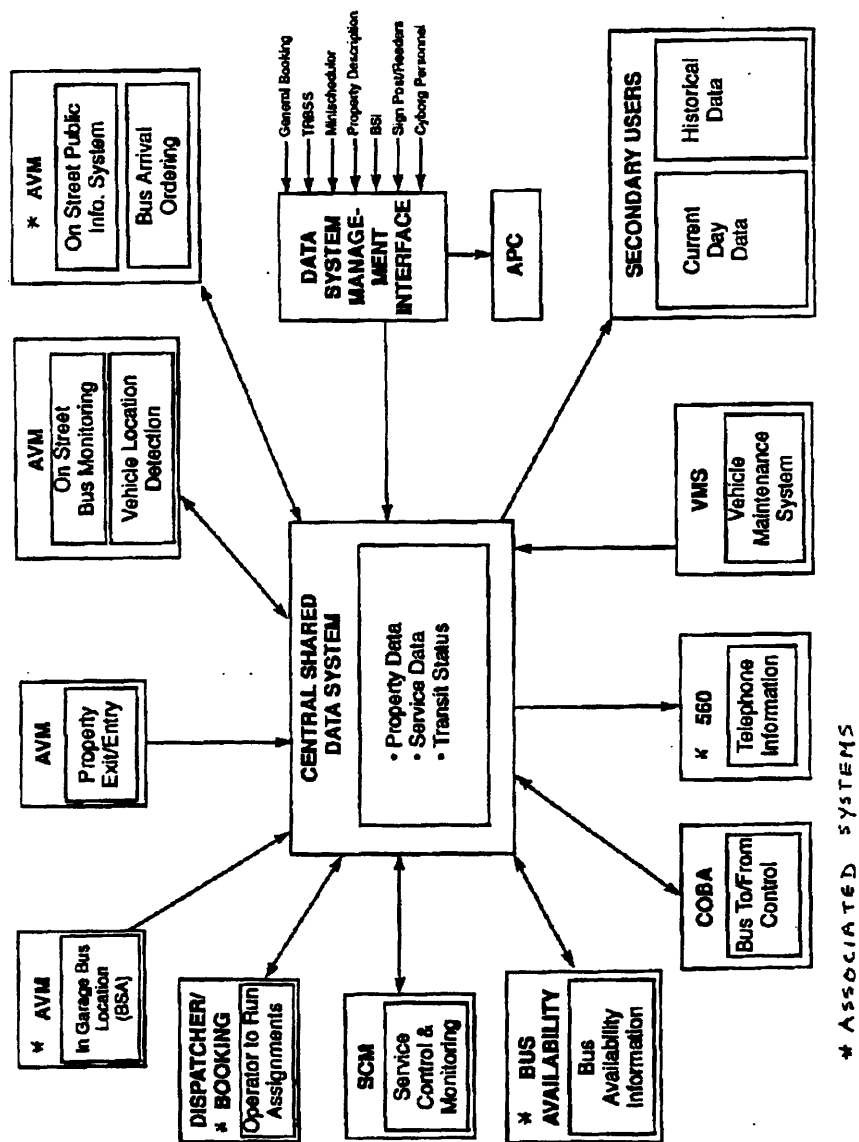
For instance, OC Transpo wanted a better way to collect data for service and operations planning so they developed a relatively inexpensive Automatic Passenger Counter (APC) system. OC Transpo also wanted a better way to convey static passenger information, so they implemented an automated home and bus stop based telephone information system called 560. There were many other small systems that OC Transpo also developed, including automated scheduling and dispatching systems.

In all of these cases, OC Transpo developed self-contained systems that were effective at solving specific problems, but without the integrated features typical of a centralized AVL system. OC Transpo has only recently begun to deploy an overall AVL system structured in a modular fashion as shown in Figure 4.3. As this figure shows, OC Transpo's interest in off-line applications did not mean that they were ignoring the application of technology to real-time functions. Their COBA communications system helped them to perform real-time operations monitoring and control, and they are currently updating COBA and integrating this module into a full-scale AVL system due to be operational soon.

Three of OC Transpo's systems are of interest in this thesis: their APC system because it contains communication and location technologies and because it represents a highly successful application of technology to service planning, their 560 system because it deals with passenger information and their Automatic Vehicle Location and Control (AVL/C) system because it deals with operations monitoring and control. The 560 and AVL/C system will be described more thoroughly because they are the systems that deal specifically with real-time operations monitoring and control and passenger information. This section

on OC Transpo ends with a discussion about the development, installation, training, benefits, and effectiveness of their individual real-time systems and includes a comparative assessment of OC Transpo's incremental disaggregate approach and the TTC's large one-system-all-at-once approach.

Figure 4.3: OC Transpo's AVL/C¹



1. Source: AVL/C: System Scope and Concepts [7]

Before these systems are investigated, however, the thesis will describe how OC Transpo was conducting these functions before technology was given a larger role.

4.3.2 Prior Methods

Prior to the introduction of these technologies, OC Transpo was obtaining most of their information in a traditional manner. Much of the operations monitoring and control was being done by 6 mobile inspectors and 18 street supervisors located at focal points. These inspectors communicated via mobile radio supervisors located at central control who make many of the control decisions. This gives central control a dominant role within the decision-making process.

Operators are also included in the operations monitoring process mostly by filling out daily reports and conducting much of the monitoring and control that would otherwise be done by field inspectors. Given printed schedules, operators are expected to follow the schedules as closely as possible, making the control system largely schedule-based, rather than headway based. Much of the passenger information was being provided by independently staffed customer service agents who disseminated information and provided assistance to passengers [Duerr 31].

Data collection was being done by eight traffic checkers employed full time to collect point, on-board and running time counts for the buses. These checkers also occasionally conducted special passenger surveys.

4.3.3 APC System

One of the agency's primary concerns with their manual data collection program was the quality and quantity of data collected by their traffic checkers. The agency decided to automate the data collection process by using an Automatic Passenger Counting (APC)

system that included location technology. Passenger counting was achieved with infra-red light heads that proved quite accurate at counting boarding and alighting passengers.

The APC system was introduced in 1978 after a decision to develop a passenger counting system was made in 1975. Originally, OC Transpo's APC system consisted of relatively crude and inaccurate location technology (exclusively odometer-based) and crude data storage and transfer technology (data stored on magnetic cassettes which would then be physically transferred), but over time and through several redevelopment periods lasting from 1978 to 1984, it has evolved into a highly effective and efficient APC system [OC Transpo 6].

To locate their buses, the agency's APC system uses signpost-odometer technology quite similar in functionality to the technology used in the TTC, except that the APC system data is not transmitted in real-time. Instead, this data is stored in an on-board processor. Whereas in the early days the APC data had to be physically transferred from the bus to the host computer, the downloading of information is now automatic. At 6:00pm daily, the main computer activates and begins polling the APC buses which do not respond until they have become idle for at least 30 minutes and can be assumed to be out of service for the day. When this condition is met, the APC equipped bus opens up a unique APC microwave channel and the data is transmitted from its data storage unit to the host computer. The transmission time for each bus takes about 1.5 minutes. This process occurs without human intervention, minimizing the risk of errors associated with the transmission of data.

On-board the vehicle, several modules, including the Passenger Counting Module (PCM) and the Radio Control Module (RCM) collect, process, store and transmit data to the host computer. The PCM receives input from the infra-red beams, the signpost-odometer system and the timer to integrate passenger boardings and alightings with locations and times. The PCM also logs dwell times, idle times, running times and times of conges-

tion based upon the above data. The RCM serves to transmit this data to the host computer at the end of the day.

After the data is transmitted to the host computer, algorithms check the validity of the data and in the absence of serious errors, automatic reports are created that summarize:

- locations and times of heavy boardings and alightings
- peak load points and times
- locations and times of congestion and delays
- schedule adherence

Specialized reports can also be generated for particular routes, times or statistics based upon specific requests.

OC Transpo's development process for the APC system has been quite successful due in part to its length and focus. Since its inception in the 1970's, the APC system has undergone many changes and improvements. Currently, there is only one full time person and one part time person required to maintain the APC/AVL equipment as well as a programmer to develop any special reports. Since the system is more or less automatic, training is not needed for either the operators of these specially equipped buses or the managers who read and analyze the resulting data. As distinct from real-time AVL systems that need equipment on all vehicles, APC data needs to be collected on only a sample of the fleet; typically about 10 - 15%.

It is clear that OC Transpo's APC system has been highly cost-effective. If you apply an industry-wide average of one data collector for every 100 operators (which is a low estimate), and an average of 1.5 operators per bus, with OC Transpo you would need about 12 traffic checkers [Levinson 40]. Given costs of about \$50,000 per year per traffic checker, the annual cost of data collection would be about \$600,000. In contrast, OC Transpo's APC system cost about \$1 million in capital cost which when spread over a 10

year life span with an assumed interest rate of 5% per year and added to \$150,000 in annual operating costs totals about \$280,000 a year. Thus the APC system costs significantly less than the manual collecting system at the same time producing much better data. With APC, OC Transpo can obtain reliable and detailed information about its routes that is simply not possible with manual techniques. An optimized schedule that can result from this data can lead to either service performance improvements or cost savings in terms of being able to run less buses.

OC Transpo's experiences with APC exemplifies a successful application of technology both to improve performance and to reduce costs. It should be noted, however, that the system's success is limited by its functionality, which is collection for off-line analysis.

4.3.4 Passenger Information Systems

OC Transpo also uses technology to assist in providing passenger information. In addition to traditional static information such as printed schedules and maps and bus stop signs and shelters, OC Transpo has the 560¹ system, an automatic telephone information system that contains information about scheduled arrival times for every trip in the system down to the bus stop level. Telephones are installed at major bus stops so that passengers can call a 560 number from the stop or from home and find when their bus is scheduled to arrive.

The 560 system has become very popular with the public as shown by a recent survey of OC Transpo users [64] which found that 20% of trips were preceded by calls to 560 with a total of 7 million calls made annually. A full 6% of interviewed riders believed that they used transit more because of 560 which would translate into a 1.25% increase in off-peak ridership. To the transit authority, 560 increases the number of transit users, induces

1. The 560 system was developed by Teleride Sage

operators to adhere more closely to schedules, allows the authority to make more frequent changes to schedule, pre-empts complaints from passengers, and reduces the load on conventional telephone services.

To the public, it fills the need for information, improves service to riders who call, and reduces perceived waiting times at bus stops. The survey also performed a cost/benefit analysis and found that the quantifiable benefits alone outweighed the costs by a ratio of 1.7 with benefits estimated at 9 cents a call and costs estimated at 5 cents a call. While these results are encouraging, they apply to a real-time system that gives out largely scheduled information, rather than information based on the current system state.

Although the 560 system is viewed as being successful, OC Transpo still saw a need to revise it. During times of heavy use, the system supervisor would not be able to keep up with the need for up to date schedules, and the 560 message structure and message content needed to be revised. In addition to solving these problems, OC Transpo also wants the 560 system to include service exception information as it becomes available so it can be made into a more responsive real-time system.

In the near future, the 560 system will take information from a shared central database that monitors delays and creates messages about service delays and service adjustments as an integral part of OC Transpo's new AVL/C system. All the special messages about service delays and adjustments will be recorded and updated each time more information becomes available and will be automatically removed when service is fully restored.

Independent of the 560 system, OC Transpo is developing a real-time bus arrival information system at several high volume bus stops called the Public Information Sign System. This system will consist of upstream readers and bus stop displays that show the order of buses arriving at high volume bus stops a few minutes before they arrive. These

readers detect and process buses using passive identification technology. The Passenger Information Sign System will also be tied into the new AVL/C system.

This system is being installed to help solve a problem that occurs at high volume stops on the agency's transitways. Buses arrive and depart at bus bays in the corridor based on a queuing system with each bus bay able to accommodate three buses. As a bus arrives, it joins the end of the bus queue (perhaps the third bus in the bus bay) with some passengers seeing its route number and boarding immediately. When the bus reaches the front of the queue, it often has to stop again to board additional passengers, typically those who arrive late or who do not identify the incoming bus because of sight restrictions. They then see the bus approaching after the crowd thins and catch it at the front of the bus queue. As a result, the bus has to stop twice to pick up passengers at the same stop, wasting precious seconds.

OC Transpo's hope is that with the new system installed, they will be able to eliminate one of the stops and thus save bus operating time which will translate into real cost savings. Customers who are at the ends of lines would be able to anticipate buses arriving via the signs and could move towards the appropriate location for boarding. Whether this actually happens remains to be seen.

4.3.5 Operations Monitoring and Control

History

Technology in one form or another has been used for real-time operations monitoring and control for quite some time at OC Transpo, reflecting the agency's philosophy of centralized service monitoring and control. A sophisticated communications system called COBA was developed in the early 1970's comprising of hardware and software providing radio communications between controllers, operators and on-street supervisors. COBA

also contained sub-modules that provided operations functions such as service exception reporting, bus-operator-run assignments, schedule database creation, operational and status data logging, data retrieval and end of day reporting [OC Transpo 52].

Although COBA had its strengths, it also had numerous shortcomings. The system did not include any automatic vehicle location data, the communication system did not allow controllers to communicate with operators on an individual basis, and there was no facility available to record the actions that were taken by controllers. In 1982, OC Transpo decided to start addressing these shortcomings by developing an AVL/C system over a series of phases as in Toronto. Phase I verified the accuracy of the hardware selected for vehicle monitoring and Phase II tested the system on one major route (Route 95). Phase III, which is currently underway, will extend the system to other routes and Phase IV will shift the emphasis from prototypes to production versions [9].

Location Technology

The location technology that is to be used in the AVL/C system is different both from the technology used in its APC system and from that used at the TTC. OC Transpo initially considered a signpost-odometer system similar to the one used at the TTC, but rejected it because of its high capital, maintenance and communication costs. The agency instead chose to use passive identification technology in which special emitter-readers are placed at strategic locations along the bus routes. These emitter-readers send out a steady RF beam that is reflected back to the emitter-reader by special identification tags mounted on the buses. The return signal contains information about the vehicle ID. This information, along with the location of the emitter-reader and the time is sent by land lines to the host computer. The locational accuracy of this setup is limited by the density of the emitter-readers. Presently, the bus network contains only about 25 emitter/readers.

OC Transpo will also use GPS receivers to supplement location information received from the emitter/readers. The GPS receivers will transmit absolute information updates to the central computer at an interval that is half the headway of the service. For instance, if the GPS receiver is installed on a bus that serves a route that has 10 minute headway service, the GPS receiver would send location information every 5 minutes. To minimize the accuracy errors of GPS, the receivers' locations are calibrated and corrected with the known locations of the emitter/receivers.

The computer then decides whether this information is useful for control. The computer makes use of certain schedule adherence algorithms that decide whether or not the vehicle needs intervention, and if it does, it reports the vehicle to the controller on an exception basis. By filtering the information, this system makes it easier for the controller to focus on priority buses.

Communication Systems

Although the communication system at OC Transpo is neither as sophisticated nor as complex as the one in place at the TTC, it is still fairly impressive. In the AVL/C system, the main method of voice communications is still via an upgraded COBA system. COBA now consists of a radio communications subsystem that subsequently provides input into the COBA data subsystem. The subsystem consists of several radio channels with each channel reserved for a particular situation. For example, one channel is reserved for operator change-offs while another is used for emergencies.

When an operator wishes to talk to a controller, he or she requests a channel and is placed in a queue based upon the priority and time of the message. The call request shows up on the controller's screen along with all the necessary information corresponding to the call, such as bus operator ID the bus ID and the route and run number of the bus. When the controller reaches the call, he or she places it in the current call position, opens up the

channel and deals with it. At the end of the call, all the aspects of the call including any actions that are taken are placed in a log file.

With the addition of the GPS technology, additional changes to the communication system will be required. Extra data channels are needed for the GPS receivers to send their data through and the system needs to be upgraded from conventional radios to digital radios. OC Transpo feels that the change to digital radios was inevitable, however, even before GPS was introduced.

Hardware and Software

AVL operations functions at OC Transpo are divided into several modules, with each module designed to perform specific tasks. Some of these modules are integrated together, but some perform independently of the other modules. The systems that utilize AVL data the most are the 560 system, the Public Information Sign System and all of the subsystems that make up the AVL/C system: the automatic vehicle monitoring subsystem (AVM), the service control and monitoring function (SCM), the COBA system and the dispatcher/booking module [52].

The modules of the AVL/C system are completely integrated and control the displays in the operations control room. At the start of each run, the bus must be initialized onto the system through the dispatcher/booking module. This module includes a schedule of operators who are supposed to work certain runs, defined as the full schedule of a vehicle from pull-out to pull-in. Dispatchers change this schedule when an operator fails to work the assigned run.

When the bus pulls out of the garage, special tag readers read the bus ID from a tag on the top of the bus and a run plate tag placed on the front of the bus by the operator. This way, the system is able to link the bus, the operator and the run numbers. At the same time, the GPS receiver transmits the bus's location and is recalibrated using the known position

of the tag reader. The information gathered when the bus pulls out of the garage is similar to that during the initialization sequence for CIS at the TTC, only in this scheme, the operator's only requirement is to place the run plate on the bus. This is similar to the philosophy behind the APC system that stresses as little required human intervention as possible. The bus, operator and run information will all be displayed in the control room if the bus is off-schedule.

The data obtained by the dispatcher/booking module provides the input to the Automatic Vehicle Monitoring (AVM) module. When a bus passes an emitter/reader and reads the bus tag or when the GPS receiver transmits location and ID, the AVM module determines the schedule of that bus by using the appropriate cross references. It compares the scheduled and actual times and stores the deviations in a transit status file only if they are beyond a certain threshold time.

The AVM module provides input into the Service Control module (SCM) which takes the data stored in the transit status file, processes it and displays the data to the controllers. This module, when fully functional will be able to show buses that are beyond a threshold level from the schedule. This module also looks for potential problems, such as emergency situations on certain street segments (entered in the central database by operators, inspectors and non-OC Transpo personnel). The module then informs controllers of these potential problems. The SCM module will also contain algorithms that detect and alert the controller to service-related problems such as gaps in service. OC Transpo wants the SCM module eventually to be developed into a subsystem that not only detects problems, but also suggests solutions.

During the run, all communications between the operators and the controllers will be controlled by the COBA system, as explained earlier. In the near future, it will have the ability to communicate with the operators on an individual basis, and will even have con-

ference call capabilities. Controllers can talk with more than one operator so that scheduled transfer meets between buses can be efficiently coordinated. All the information that “pops” up on the controllers display when operators send messages comes from these modules.

The information from all modules are integrated and displayed on the controller workstations which consists of a VAX client running under the VMS operating system and networked through Ethernet. The graphical displays of schedules, messages, bus locations, operator and bus ID's, emergencies and service irregularities are all displayed using X Windows as the Graphical User Interface (GUI). Windows pop up and sounds emit whenever the SCM detects a situation or whenever messages go through to the controller. Controllers can easily access multiple windows of information and zero in on the windows containing the highest priority information with this GUI. There is also a microphone for voice communications and a channel switcher.

Human Factors

Similar to CIS, OC Transpo's systems have caused many changes in the way users perform their duties, although operators have not been affected significantly since the design philosophy has been to minimize the changes imposed on indirect users. Thus operators need to know little about the AVL/C system, nor do they really have to change their work habits, except in the use of alarms and the possibility of more control commands issued by controllers. Unlike CIS, OC Transpo buses will not have an operator display unit - the radio equipment will largely remain the same and the only elements that are to be added to the buses will be the emergency alarms, the GPS receivers and a radio control unit.

The inspector's duties would be simplified in one respect but complicated in another. On one hand, most of the control actions would now be done by central control. The

inspector's post-AVL responsibilities would be reduced to validating data about locations and ID's coming in and to taking care of emergencies and other disturbances that occur within their area. On the other hand, inspectors would have to log all emergencies and disturbances that occurred for the SCM module to be effective.

Controllers would see the greatest changes from these systems. As in the TTC case, there is evidence that they should be able to make better control decisions with the aid of the AVL/C system, but they might also be deluged with information. The planners and managers would be able to receive more frequent, more complete and better information from the AVL/C system. The APC information has proved to be beneficial and it is anticipated that the AVL/C information will increase these benefits. They would also reap the benefits of better on-time performance and reduced headway variations due to the AVL/C system. The human inputs into AVL/C are shown in Figure 4.4.

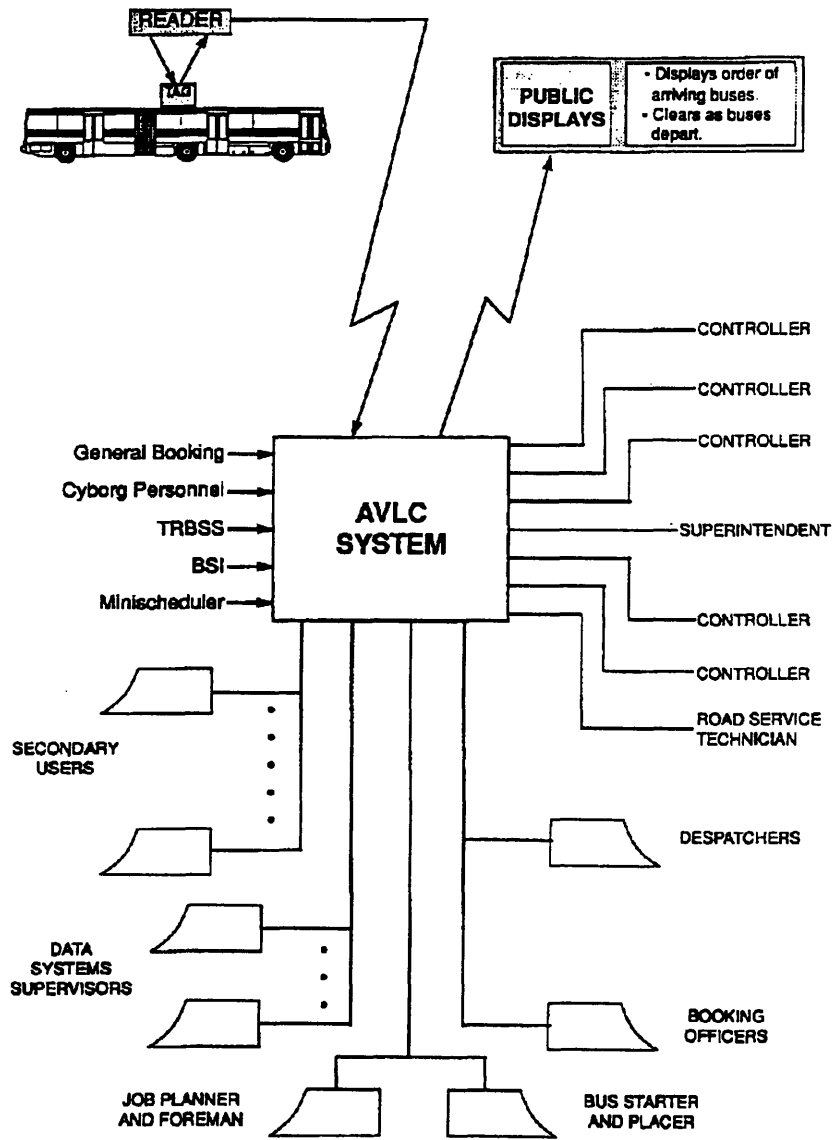
4.3.6 Costs

The only estimates of AVL/C costs that were available come from Peter Van der Kloot, Management Information Systems (MIS) project manager at OC Transpo. These estimates are rough, but give an indication of the costs associated with OC Transpo's AVL/C system.

Mr. Van der Kloot estimates the hardware, software and installation costs of the AVM component (primarily the passive identification system) to be about \$2 million CAN. The SCM component costs, which include the workstations for the controllers and the hardware and software to handle all of the information is estimated to be about \$2.5 million CAN. Mr. Van der Kloot also estimates that costs will be incurred in the scheduling, booking and maintenance systems modules because of necessary software reprogramming to

integrate with and conform to the rest of the AVL/C system, but the extent of these costs are not known at this time.

Figure 4.4: Labor Inputs Into AVL/C¹



In addition Mr. Van der Kloot estimates that 4 - 6 full time positions will be required to ensure data accuracy and to provide an on-line link to passengers who register complaints.

1. Source: OC Transpo [49]

At a cost of about \$45,000 per position, this portion of AVL/C would incur an ongoing cost of about \$270,000 per year. On the vehicle, GPS receivers are estimated to cost about \$600 - \$700 per receiver, but GPS costs increase if a digital radio system is included. Overall, Mr. Van der Kloot estimates total AVL/C costs to run about \$7,000 to \$11,000 per bus, which will be somewhat lower than the per-vehicle costs for CIS. This is not surprising since the AVL/C system has a less advanced communications system, a less dense network of signposts, and a much less advanced operator interface than CIS.

4.3.7 Development, Installation And Training

OC Transpo's approach of developing one system at a time means that development, installation and training become easier to manage. The system development time for both the APC and 560 systems were small compared to CIS albeit with much lower levels of functionality. Since many of these subsystems require little direct human interaction, training requirements are also minimized.

The AVL/C system is proving to be a different story, however. Initial stages of OC Transpo's AVL/C went fairly smoothly, but development is currently behind schedule. Many of the sub-systems that make up AVL/C have been developed and tested, but problems are occurring in integrating the entire system. The AVL/C system was supposed to be fully operational in 1993, but full-scale implementation has been delayed twice. Currently, OC Transpo is "beta-testing" their current version of AVL/C and expects to have their final version operational by Fall 1994.

One of the problems may be due to a lack of experience in integrating large-scale systems. Another reason for the delays may have been the loss a year ago of OC Transpo's former general manager who provided critical vision and leadership in guiding OC Trans-

po's technological initiatives over the previous twelve years, and even though his philosophy is still applied in the agency, his leadership is probably missed.

4.3.8 Overall Effectiveness and Comparative Assessment

The AVL/C system, when it is installed, has the potential to be very effective and even without full vehicle location capabilities, the system is proving to be useful. Incidents are handled promptly and the links in the database that connect the bus and its scheduled location give controllers an indication of where the bus should be which is better than no information at all. When the AVL component is operational, the system will become more effective. The logs of incidents and controller actions will help in evaluating the effectiveness of control strategies. Logs are not currently part of the TTC CIS system.

Many of AVL/C's sub-modules, including the 560 and Passenger Information Sign System have been developed in parallel with each having a stand-alone capability consistent with OC Transpo's incremental development philosophy. With a modular approach to system design, you also have more chances to modify your systems later in the development process. If one sub-system does not suit OC Transpo's requirements, the losses of redeveloping a module or coming up with a new module is less than modifying the entire integrated system.

The disadvantage of developing small systems that are integrated together later is that the integration process may be difficult. You have to resolve compatibility and functionality issues and if two systems overlap and perform a common function, duplication will occur. Conversely, new systems might have to be developed in order to perform functions that have not yet been defined. These problems are not as noticeable when you start designing a fully integrated system, as the TTC has done.

In general, the problem of integration has not been serious at OC Transpo save for a few systems. Some modules, such as the bus location, AVM and SCM integrate fairly well. For example, when a bus passes a signpost, one module is responsible for locating the bus and identifying it. This information is then passed to the AVM module which identifies the bus and hence the operator, run and schedule. The Service Control Module (SCM) then takes this data and determines whether or not it gets sent to the controller. In this example, information flows directly and automatically from one module to the next.

Such clear linkages do not always exist, however, as is the case with the 560 passenger information module. The 560 controller receives reports from AVL/C but then must manually input changes to messages sent out over the 560 system, severely constraining its real-time update capabilities. On a bad weather day, it probably would not be possible for the 560 system controller to keep up with all the delays that AVL/C generates. Manual inputs are relied upon because the two systems are incompatible making it very difficult to update 560 automatically from AVL/C.

OC Transpo's AVL/C system differs from TTC's CIS system in several respects. In terms of location technology and communications, AVL/C provides less information and utilizes simpler technology. Ottawa's location technology is discrete (accurate to the nearest signpost and updated by GPS every half-headway) rather than continuous and its reporting strategy is exception based instead of poll-based with software used to filter out unnecessary information.

This has two important implications: much less information is being sent to the controllers, and the information being sent is less detailed. This configuration has both advantages and disadvantages. By showing only vehicles that are off-schedule, this system helps prevent information overload and lets controllers concentrate on only the most important information. By doing this, though, the system may fail to present information that might

be useful in some situations even if it were not useful in all situations. Controllers can train themselves to filter out useless information over time and only look at that information in special cases, but it is harder for software to do the same thing as effectively.

Cost is likely to be another advantage of this configuration because there is less required wireless communication capacity since land lines are primarily being used and less information is being transferred and processed. The only wireless communications are for voice communications and GPS transmission and this only happens on an exception basis or at infrequent intervals.

OC Transpo's discrete location system may lead to inaccuracies for locations between signposts and perhaps incorrect decisions as a result of that inaccuracy, although GPS updating partially addresses this weakness. This may not be a large disadvantage, however, because many of the signposts are located in the busways where there is little congestion and low variability of travel times. In the busways, this configuration may well be sufficient.

AVL/C also differs from CIS in the way that operators are involved. At CIS, operators are required to sign on every time they start an assignment. While this may give the operator a sense of security by knowing someone is monitoring them, it also can introduce error into the system. If the operator forgets to sign on, the trip does not exist until the controller reminds the operator to sign on. In AVL/C, this sign on procedure is automatic, taking the operator "out of the loop" and eliminating this source of error. Operators at the TTC have more responsibility and are also given more information, including schedule adherence. This helps shift partial control responsibility to a local level with the fallback of additional controllers at central control. AVL/C does not have this capability.

In terms of hardware and software, in general CIS is probably more advanced than AVL/C, but AVL/C does have some advantages over CIS. On the vehicle, the TRUMP

units that are an integral part of CIS provide a superior interface for operators. This unit gives the operators many opportunities to report incidents or adjust their speeds before the controller will suggest speed adjustments to them. This unit gives operators a lot of leeway, to which they have responded positively.

The interfaces at the control room, though, are a different story. The X Window interface that AVL/C will incorporate is likely to be more effective than the three screens used in CIS. With this interface, controllers are able to customize their screens and prioritize their information by putting the most important information in a foreground window while relegating less important information to the background. Controllers can easily switch from one window to another using a mouse, thereby increasing their efficiency. On a CIS workstation, inputs are via multiple keyboard entries that are sometimes cryptic.

This windowing system also allows more information to be placed on the screen than the CIS system leading to the CIS three screens per workstation while AVL/C requires only one. This is not really a fair comparison, however, since AVL/C does not graphically depict bus locations and only shows incidents and buses that are not on time whereas CIS displays graphic locations for all vehicles.

The X Window interface also has its disadvantages. Since there are no graphical displays, controllers have to envision and estimate the location of the bus, probably requiring more experience in the field to function effectively. Also, by putting some information in the background, controllers might miss some information. Important information may be updated in a background window, but it might not be shown since a foreground window could obscure it. This problem may be mitigated by software that prioritizes information and pops windows into the foreground based on that priority.

4.4 London Transport

4.4.1 Introduction

In both Ottawa and Toronto, the agencies responsible for providing transit service operate as single public entities, responsible for all planning and operations within their defined service areas. When new technology is introduced, it can fairly easily be implemented on a system-wide basis since all of the transit operation responsibilities belong to the one operating authority. The situation in London (and in the rest of the U.K.) is rather different and adds complexity to the introduction of new technology.

In London, public transportation is operated in an increasingly privatized environment, although service is still subject to central planning. In London, many separate entities provide transit service as contrasted with the single operating entities in both Ottawa and Toronto. This environment provides both opportunities and complications when it comes to implementing new technologies. Decisions about technology must take into account this environment. This case study describes the operating environment in London and its effects on technology implementation.

London Transport has always been a leader in technology implementation, researching, testing and implementing a myriad of advanced technologies to aid them in their operations since the early 1970's. They have employed and tested a variety of location technologies, operations monitoring and control systems and passenger information systems. London has preceded most efforts in North America and have been on par with similar developments in the rest of Europe and in Japan. Currently, London Transport is developing and implementing a real-time passenger information system called Countdown that provides up to the minute arrival information at selected bus stops. This case

study focuses on the Countdown system and the operational environment in which Countdown must operate.

4.4.2 Institutional Arrangements in London

In 1985, Parliament passed the Transport Act which effectively deregulated bus service outside London. As a result, in many parts of the United Kingdom most public transportation services are provided by private or “corporate” entities which have replaced the pre-existing public authorities and must operate on a commercial basis. In this scheme, all commercial aspects of service provision and production including system planning, service design and operations are in the hands of the private and corporate sectors. The role of government planning agencies has been reduced to determining residual non-commercial services which are awarded based on a competitive bidding process. Controls over fares, markets served, employee and equipment standards and entry and exit have been eliminated, leaving only safety regulations [Mantell 42].

This has caused many changes within the U.K. industry: fares have increased, labor costs have decreased and service has generally increased. There have also been some significant negative effects, notably a drop in ridership, a lack of system-level public information about services and also a lack of fare and service coordination. This lack of coordination combined with cost-minimizing objectives of many operators would tend to hamper efforts to implement technologies on a system-wide basis.

The situation within London proper is different since it has been exempted, at least temporarily, from deregulation. In this region, London Transport, which is the agency responsible for providing or securing public transportation for the Greater London Area, retains its dominant role in determining service provision and through its subsidiaries, London Buses (LBL) and London Underground (LUL), in direct operation. The environ-

ment within London is thus a regulated one, with LT determining all routes and fares and LT subsidiaries operating the majority of bus routes. The rights to operate bus routes are tendered in a competitive bidding process in which LBL subsidiaries compete with private operators.

Contracts are awarded for three years and contain many requirements. The winning bidder who operates the route must adhere to requirements on route alignments, service levels, scheduled frequencies and fare structures. LT makes sure that these requirements are met by requiring the operator to report lost mileage, fitting contractor vehicles with tachographs, monitoring the operator's performance against timetables using roadside checks and reviewing complaints from customers.

In return for operating a service, the contractor is reimbursed for agreed costs and is allowed a profit margin. Fares are specified by LT and the contractor also must accept all Travelcards and passes. All fares that are collected are remitted to LT. Contractors must provide their own buses which must conform to vehicle specifications set out by LT, and also must display the LT symbol.

On routes run by private contractors, London Transport still plays a large role with the Tendered Bus Division of LT being responsible for accounting, contracts and administration. The division also looks at planning, marketing, operations and monitoring/safety of the privately operated routes to make sure that the contractor is adhering to standards. By the end of 1991/92, 38 percent of the bus network had been contracted out with LBL subsidiaries retaining responsibility for the remaining routes. In this more competitive environment, service quality has improved, ridership has increased and both costs and subsidies have decreased. Since bus operation in London is still largely regulated with contractors subject to close LT oversight, system coordination has largely been maintained.

In the longer term, the Conservative government intends to deregulate public transportation in London, however currently the only active step being taken is the full privatization of the LBL operating units. Many of London Transport's newer systems have been developed in this environment [Mantell 42].

4.4.3 Prior Systems and History

The history of London Transport's dealings with automatic vehicle location systems began in the early 1970's when they began testing odometer-based techniques [Hamilton 32]. At that time, most of the devices were seen as experimental and did not have widespread use. In the early 1980's a system called BUSCO was developed initially to provide service control using AVL technology on route 36 [Balogh 11].

In 1984, Steer Davies & Gleave Ltd. [68] examined bus travelers' perceptions of real-time information in London, England. This survey was done to evaluate the effectiveness an experimental real-time passenger information system that displayed, at key bus stops, the arrival times of buses in minutes. The respondents were asked questions about information displays, perceived and actual waiting times at bus stops and attitudes towards displayed real-time information. The first finding was that with no real-time information at bus stops, passengers perceived a good deal of uncertainty about the arrival of their intended buses, even with knowledge of schedules. They also tended to over-estimate actual times spent waiting for buses. The second finding was that passengers were willing to accept a modest increase in fares in order to receive real-time information. A third finding was that real-time information tended to counteract the over-estimation of actual waiting times for buses. The results suggested that passenger information caused a decrease in perceived waiting times.

The Steer, Davies and Gleave study also found that passengers would likely change their travel plans in cases of long service delays. Three quarters of the passengers were prepared to wait up to 10 minutes for a service scheduled to run at headways of 6 minutes. For waits of over 20 minutes, most thought that the wait would be too long and would consider other travel options. Passengers also felt that knowing when buses will arrive makes time pass faster and increases their likelihood of using bus transportation. All this in spite of a significant majority believing that there was the chance that the information would not be completely reliable.

In a conjoint trade-off analysis which involved fares, frequency and information provision, it was found that information about the arrival time of the next bus was valued at 25% of the average bus fare while more comprehensive information such as the load on the bus, its destination and information about multiple buses was valued at 45% of the average fare. Further analysis suggested that one-half of the waiting time penalty disutility could be eliminated if information on the next bus was given to the passenger. Better information would further reduce this disutility. These results can be questionable, however, since stated preference data, rather than revealed preference data was used.

Another stated preference study conducted by Colquhoun Transportation Planning [16] also looked at how much information systems would be worth to passengers. In addition to the qualitative measures of worth, the study tried to measure quantitative worth in monetary terms. The study found that bus users do perceive a benefit in electronic displays at bus stops and are prepared to pay more for more accurate information, but there is a diminishing utility for the information as it increases in accuracy. There was also some evidence that the value of information increases as service frequency decreases. The study does admit, however, that their stated preference techniques and data cannot be guaranteed to provide robust coefficients and valuations, and that the benefits may be overstated. They

recommended policy evaluations along with other combinations of techniques in order to validate the results of this study.

Silcock [59] conducted passenger surveys for passengers of the Northern Line of the London Underground and passengers using the bus system at Heworth (outside Newcastle-upon-Tyne in the UK). Both of these transit routes had some sort of real-time passenger information systems, and the focus of the survey was to determine the benefits that these information systems provided. The information system in the Northern Line provides order of arrival, destination and expected arrival time information of incoming trains at each station.

One of the main impacts of this system was an increase in accuracy of passengers' estimated waiting times. Normally, passengers would overestimate their waiting times, but this system reduced their estimates somewhat. On the average, passengers saw an 0.68 minute reduction on their perceived waiting time in a typical wait of 3 to 4 minutes. Using a price elasticity of demand of -0.17, Silcock estimated that ridership would increase by 1.04 million passengers annually, amounting to a revenue increase of 0.57 million pounds per year.

In 1986, a passenger information system was added to BUSCO making use of the AVL data and featuring electronic signs at 10 bus stops. The software included algorithms using the prevailing speeds of the buses to forecast bus arrival times at stops. The electronic signs showed the destinations and estimated arrival times of the buses, in minutes. After a bus passed a stop, the algorithms and signs would reset in a process called a clear-down.

In 1992, the Transport Studies Group at the University of Westminster, London [22] conducted a survey looking into user perceptions of a real-time passenger information system installed on the Riverbus system in Canary Wharf. Riverbus is a premium commuter boat servicing Canary Wharf, Chelsea Harbour, Cadogan, Charing Cross-St. Katherine's

Dock and Greenwich. The passenger information including the time and estimated arrival times of the next three boats and their destinations is displayed on screens at entrances to jetties and in waiting rooms. The main result of the study showed that almost half of the frequent users of Riverbus did not use the passenger information system. This was attributed to the good on-time performance of the commuter boat and the good static information system that was provided.

Most recently, London Transport decided to conduct another trial on another bus route, this time using more advanced technology and algorithms. This demonstration project was named Countdown and the system was applied to route 18, a 16 km route which operates 33 buses at 6 minute headways. Half of the 100 stops associated with route 18 were fitted with Countdown signs. Countdown is the first trial of the Passenger Information at Bus Stops (PIBS) project that is intended eventually to provide real-time passenger information throughout much of the London Transport network.

4.4.4 Location Technology

The technology used to locate vehicles in Countdown is a classic signpost-odometer system using small microwave beacons mounted on lamp-posts at about 50 locations along the Route 18 right of way. These battery-powered units transmit their ID which is received by an on-bus reader which is then sent along with the bus ID, the wheel rotation count from the odometer and any other relevant information back to the control room over the London Buses Band III radio system. All buses are polled every 30 seconds by the central computer. On several other routes beside Route 18, the same AVL system is used, but with a lower density of signposts, since the location information is used only for service monitoring and control. Route 18's Countdown system, however, needs this AVL

data for its passenger information system and hence the need for a higher density of beacons.

4.4.5 Communications Technology

Most of the communications technology used for Countdown is fairly standard. The beacons transmit their identifications by microwave and the bus transmits its information over LBL Band III radio frequencies. The electronic signs that are installed at the bus stops showing arrival information receive their information over land lines. A schematic of LT's Countdown system within the AVL system is shown in Figure 4.5.

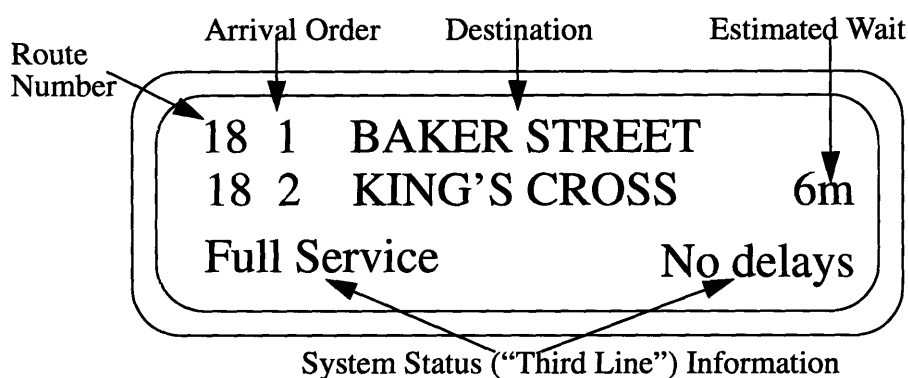
4.4.6 Hardware and Software Technology

For Countdown, the hardware and software needs are geared towards serving the passenger, rather than serving controllers. Like many centrally controlled and processed AVL systems, LT has a central computer that receives, processes, controls and then transmits relevant AVL information. The basic real-time input to this central computer comes in and is then processed using an algorithm that estimates bus travel times [Marguet 43].

The algorithm estimates the theoretical arrival time (TAT) of a bus at a stop by adding the actual departure time of a bus (ADT) to the sum of "learned travel times" (LTT's) at a certain time period for all travel links between the bus and the stop. The "learned travel time" takes into account previous estimates of "learned travel time" and actual travel times (ATT's) of recent bus journeys. The algorithm is a simple attempt to adapt to changes in travel times due to changing traffic conditions which are reflected in the journey times of previous buses. This estimate is then transmitted by land lines to the electronic sign at the intended bus stop.

The signs use LED technology and display three lines of information including the destinations and estimated times to arrival for the next three expected buses. The signs can also be programmed to show routine information about other routes or they can show real-time messages sent by the service controller in any special circumstances. The signs are either hung on the underside of roofs of bus shelters or are stand alone displays at bus stops. An example of a Countdown information display is shown in Figure 4.6.

Figure 4.6: Example Countdown Display¹



Although the primary use for this AVL data on Route 18 is for passenger information, provisions are also made for service control. In the garage that controls Route 18, a workstation that is connected to this AVL system displays the times that buses pass beacons. Although this information provides relatively simple information for controllers to use, there is potential to expand the service control aspects of Countdown, and the Countdown system is currently being redesigned to provide better decision support for controllers.

4.4.7 Human Factors

In the operations monitoring and control (OMC) function, the primary user of computer information is the controller, whereas in the Passenger Information at Bus Stops

1. Source: London Transport Brochure [27]

(PIBS) function, this focus shifts to the passenger, although the controller does still interact with the computer system.

Like the operations monitoring and control systems at Ottawa and Toronto, operators play a relatively minor, but important role in LT's Countdown system. At the beginning of each trip, the operator has the responsibility of logging on and entering the trip number and bus destination which are then sent over LBL Band III radio to the central computer. This is required for the computer to initialize the bus into Countdown. Other than this responsibility, Countdown has relatively little effect on operators [27]. It was theorized that PIBS might cause operators to be more diligent in maintaining their schedules, but there is little hard evidence yet to support this hypothesis.

Inspectors in the street have become controllers in the control room with radically different responsibilities. Controllers now have the added responsibilities of entering in special messages to be displayed in the bus stops when circumstances warrant this and monitoring Countdown system performance.

The main effect of Countdown is on the passengers. Physically, their function does not change at all - they still wait at bus stops, pay their fares and travel to their destinations. The manner in which they wait at bus stops and their perceptions while waiting changes with Countdown, however.

4.4.8 Costs

The cost of the Route 18 Countdown trial is estimated to be about 1.4 million pounds (\$2.1 million US) [27]. While this would be a very high figure on a per bus basis, it includes all associated development costs, and expansion costs on a per bus basis should be significantly lower.

LT recently conducted such a cost estimate for one of Countdown's planned expansions to an area known as Nag's Head [Director of Planning 30]. The proposed Nag's head scheme encompasses 12 routes and 3 different operators and about 350 buses, some of which have AVL equipment already installed. The scheme also involves 20 beacons and 150 shelters. This cost estimate is summarized in Table 4.4.

Cost Category	Pounds	US Dollars ^a
Vehicle Equipment and Software	360,200	540,000
Field Hardware (signposts)	124,800	187,000
Bus Stop Hardware, Software ^b	859,400	1,289,000
Central Control Hardware and Software	60,000	90,000
Development	50,000	75,000
Misc. and Project Mgmt. @ 15%	293,153	440,000
TOTAL	1,747,553	2,621,000
Annualized Capital Costs	291,159	437,000
Annual Maintenance and Fees	360,795	541,000
Total Annual Cost	651,954	978,000

Table 4.4: Cost Estimate for Nag's Head Scheme

a. The exchange rate is based on an estimate of 1 pound ~1.5 UD Dollars

b. Not including bus shelter construction costs.

A large proportion of the costs of this passenger information system are attributable to the bus stop hardware and software costs which make up almost 50% of the total capital costs. Vehicle equipment, which made up about 60% of total costs of CIS, by comparison only accounts for 21% of the capital costs in this case.

On a per bus basis, with about 350 buses operating in this scheme, capital costs turn out to be about \$7,500, which is lower than the average cost of an AVL system and much lower than the per bus costs of Countdown on Route 18. The per-vehicle costs may understate the true costs since some of the buses in the Nag's Head scheme already have some of the necessary AVL equipment installed.

4.4.9 Countdown Effectiveness

During the Countdown Demonstration project, London Transport managed to gather a significant amount of data on the Countdown system and its operations. Much of this data was used to evaluate Countdown, with the results as summarized below [10 and 30]. Measures were developed for system reliability and availability, accuracy of countdown forecasts and clear-down and benefits of the system. Passenger surveys were also conducted to determine the value of Countdown to passengers and to assess passenger attitudes towards Countdown. The operator's view was also taken into account.

To measure reliability, LT measured the percentage of time (over a 4 week period) that Countdown was on-line and available for use and compared the results with predefined targets. Reliability was also measured for sub-components of Countdown such as the signs, the buses and service control. The results (see Table 4.5) showed that in all but one of the sub-components (service control), the targets were met.

To assess accuracy, LT collected data at 25 stops covering 1379 bus arrivals and determined the percentage of times that forecast arrival times were within x minutes of actual arrival times for different forecast horizons. The results are shown in Table 4.6 along with the targets (shown in parentheses).

Availability Category	Bus and Sign Details	Actual (%)	Target (%)
Overall System Availability		99.2	99.0
Service Control		94.0 ^a	98.5
Individual Bus		99.9	99.0
Individual Sign	17,18,19,36,66,67,71 16,25,65 70 20 Remainder	99.1 92.9 78.6 ^b 74.7 ^c 100	96.0
Overall Sign		98.8	98.5

Table 4.5: Component Reliability and System Availability of Countdown

- a. Includes a period of 30 hours downtime due to a fault on the external FTNS X25 network
- b. Awaiting a modified component
- c. Fault on external BT private circuit

Forecast Interval	+/- 1 minute	+/- 2 minutes	+/- 5 minutes
1 - 5 minutes	~60% (90%)	~85% (99%)	~99% (100%)
6 - 10 minutes	~40% (75%)	~70% (90%)	~97% (99%)
11 - 20 minutes	~35% (60%)	~50% (75%)	~90% (95%)

Table 4.6: Countdown Forecast Accuracy

The results show that Countdowns were accurate to +/- 1 minute 50% of the time, +/- 2 minutes 75% of the time and +/- 5 minutes 96% of the time, which fell short of the pre-defined targets. The report noted that the targets were set at a high level without any prior knowledge of what might be achievable. A target was set that 90% of clear-downs should be within +/- 1/2 minute of bus presence at a stop. Actual performance showed that only 65% of all clear-downs were within the target while 80% were within +/- 1 minute and 90% were within +/- 2 minutes. The report noted that performance could be improved if additional beacons were installed at bus stops.

LT also gathered data on revenue collected on Route 18 before and after Countdown was installed to the route and these results were compared with other nearby routes for control purposes. This analysis did not show a statistically significant increase in Route 18 revenue as a result of Countdown. A trend analysis for Route 18 did suggest a small increase in revenue, starting at about the time when Countdown was introduced, but there was no significant difference between the changes in Route 18 revenue and the changes in the other control routes. While the results showed that Route 18 performed a little better than the other control routes, the report conceded that the improvements were likely due to service disruptions that occurred on the control routes due to disputes over staff working conditions.

These results were somewhat surprising given the results of the attitudinal and valuation survey which predicted a net increase in patronage of between 10% and 12%. In that survey, 30% of respondents said that they now travelled more frequently and 4% said that they travelled less frequently. The predicted increase in revenue was obtained from a passenger survey which dealt with bus service quality and levels and patterns of patronage and revenue, along with studies of passenger behavior at stops, an ergonomics survey on the bus stop sign design, an attitudinal survey and market research [Accent 2]. The passenger response to Countdown was quite favourable. The comprehension of the signs was good and they were consulted frequently. Many thought that the design, layout, positioning, brightness, and information of the signs was adequate.

Perceived waiting times were reported to be shorter (65% thought waiting times were shorter) and the anxiety usually associated with waiting for a bus was reduced (90% thought that Countdown made waits more acceptable). Some passengers were observed to undertake other activities while waiting for a bus such as making small purchases in local

shops. The signs also allowed some passengers to forego a crowded bus if another one was coming shortly.

In conducting their market research, LT performed a stated preference analysis that was designed to gain information on the passengers' "willingness to pay" for Countdown information. The survey concluded that on the average, passengers valued Countdown at 26 pence per journey (or about 40 US cents) and were willing to pay 20 pence (30 cents) per journey for Countdown information. This was higher than expected and higher than the values used in the project justification studies. To confirm the survey results, LT modified several parameters of the survey including the questions and the survey recruiting process. In each case, the results turned out to be similar.

The staff generally gave favourable remarks about Countdown with only a few adverse comments. Operators have a few additional tasks and some regret the loss of face to face contact with route inspectors. The service controllers have had some difficulty in inputting and deleting messages, but these difficulties were considered minor. The staff also had some difficulties with the radio system, including polling failures which lead to reduced forecasting accuracy, and "crashes" in which both the AVL system and Countdown are lost. In general, however, management and staff attitudes are very supportive.

This report shows that passengers generally favor a Countdown-like system and appear to be willing to pay a premium for this service, although there is no concrete evidence that it actually increases ridership. Based on the initial Countdown success on a single route and market surveys showing the potential for further success, difficulties may arise, however, in implementing Countdown system-wide in London's complex operating environment let alone beyond London under full deregulation. Despite these difficulties, LT is proceeding with system-wide implementation of Countdown, starting with Edgware

Road (6 routes, 196 buses and 2 operating units) which is now operational and the Nag's Head scheme (involving 12 routes, 350 buses and 3 operating units) slated for next year.

4.4.10 Technology Implementation In a Deregulated or Privatized Context

A deregulated or privatized environment creates both opportunities and challenges for operators considering introducing new technology. Operators are likely to face less bureaucracy, thus implementation decisions may be made more quickly. Also, operators are more likely to advertise their new systems aggressively in order to entice more ridership.

A deregulated environment, however lacks stability and coordination. If new systems are implemented, they may only apply to the particular route or set of routes which the operator runs. You then have the problem of multiple operators installing different and often incompatible systems. In a multi-system environment, passengers might get confused over the different information provided by multiple systems and controllers will have difficulty co-ordinating connecting services which belong to another operator and are controlled by a different system.

In addition, in a deregulated environment, technology is more likely to be evaluated on a purely financial basis that may not take into account social benefits. This may result in technology being implemented only on routes where it is financially cost-effective to do so. In the mean time, operators may ignore implementing technology on their less profitable but perhaps socially desirable routes.

In London, with competition for the market rather than in the market, the situation is different. Since the provision and production of services is regulated, system coordination is still achievable. LT might help to oversee and perhaps aid in the installation of a network-wide PIBS system and with a public stake involved, public financial help is more

likely to be available. LT makes sure that either the same PIBS systems are installed throughout and if operators prefer different AVL systems, they all can function with the common PIBS system.

Another problem which may arise is the possible reluctance of private firms to implement new systems if their contracts do not specify or encourage new system development. Contracts which only run for a short term may discourage capital investments of new technology since benefits may not be realized in the short term. Also, contracts that only specify minimum levels of service which can be achieved without the need to resort to new technology can also discourage investment.

Contracts can be written, however, to encourage technology investment by either requiring cooperation in development or by rewarding increased service performance. London Transport is in the process of changing from a gross cost for of contract to a net cost one. In a gross cost contract, the operator is reimbursed for its costs and thus the operator has no direct financial incentive to improve service effectiveness. As long as the operator runs the route efficiently and meets minimum standards, the operator need not worry about ridership. A net cost tender, however, pays operators a smaller fixed subsidy amount and allows operators to keep all revenue, thus ridership becomes an important concern for them and new technologies that may increase ridership and consequentially profits could become more attractive in this contract environment.

Because of the issues described above, there are many challenges associated with implementing PIBS in a multi-operator context including:

- The initial investment required for a basic Countdown system is high, thus private operators may be reluctant to install this system without subsidy assistance from LT.
- Coordination between systems may be difficult without guidance or planning from a central authority.
- Even with coordination, in a competitive environment, competitors may be tempted to misinform passengers about competing routes in the extreme case, or similar

information may be duplicated in different systems in different forms thereby confusing passengers.

To prepare the way for systemwide PIBS implementation, the Corporate Planning and Policy Division of LT Planning suggested a structure to tackle these challenges [53].

To address the first problem, LT suggests that a Public Transport (PT) authority be responsible for planning and providing the basic PIBS infrastructure which would then be leased to the private operators. To address the second and third problem, LT suggests that the authority should also be responsible for regulating the PIBS system and network, making sure information is standardized and operators are provide correct and consistent information with as little duplication as possible. The suggested roles and responsibilities of the parties associated with Countdown in this structure are shown in Table 4.7

In this structure, London Transport (or a newly created central public authority) would be fully responsible for PIBS infrastructure, maintenance and information. This allows displays and information to be standardized for all routes that provide PIBS. The private operators would be responsible for providing AVL information through their own AVL system and ensuring service control, which would be subsequently monitored by LT.

Group	Role	Motivation
Public transport authority	Is responsible for the provision of a PIBS system	Improves information for bus passengers in line with a general policy to improve public transport
	Provides and maintains basic PIBS infrastructure	Overcomes barrier of high initial capital cost for operators
	Owens PIBS infrastructure and offers it for rent to operators	Ensures multi-operator access and avoids duplication of infrastructure
	Regulates use of PIBS system	Ensures good, consistent and comprehensive information, including network information functions
	Enables the use of PIBS system to operators	Encourages the development of a complete PIBS network
Bus operators	Rent equipment and provide PIBS on bus services	Brings revenue gain by providing value added service
	Operate AVL service control	Improves bus service performance, thereby improving revenue
	Operate PIBS system, providing route-specific (or operator-specific) information	Provides enhanced service to passengers inducing revenue gain by pricing up and/or revenue gain generating revenue
	Provide real-time public transport network information	Contracted by PT authority to carry out certain network information functions
Passengers	Willing to pay higher fare for bus services with PIBS	Receive benefits from PIBS
	New passengers bring generated revenue to operator and satisfy PT authority aims on accessibility and transfer from private transport	Perceived (and real) improvement to bus service attracts new passengers

Table 4.7: Roles and Responsibilities of Parties Associated with PIBS^a

a. Source: LT Planning [53]

PIBS information is only as good as the AVL information given to it however, thus to ensure quality information, AVL information standards could be created and operators who subscribe to PIBS information would be required to adhere to these standards. To aid operators in adhering to standards, operators could subscribe to a centrally developed AVL system that already meets these standards. Private operators could pay for the use of the central AVL system through leasing agreements. [Wilson 70] Private operators would

have flexibility in providing any extra passenger benefits they wish that is not governed by the standards.

Before PIBS is implemented systemwide, private operators have to be convinced of its true benefits and potential. If the potential is not realized, the operators have to be somewhat insured against failure.

4.4.11 Overall Countdown Assessment

London Transport's evaluation of Countdown revealed three key findings:

1. Countdown and cleardown accuracy is not at predefined levels.
2. Ridership analysis is inconclusive. There is no significant difference in ridership changes between the Countdown route (route 18) and other nearby control routes.
3. Passenger perceive benefits from Countdown. Passenger wait times seem to be shorter, passengers are less stressed at stops and passengers are willing to pay up to 20 pence per journey for Countdown information. These valuations should lead to a 10 - 12% increase in ridership.

The first finding tells us that even though Countdown accurately predicts arrival and cleardown times in most cases, it does not meet the high predefined standards. The prediction algorithms used to predict bus arrival times could well do better if they were more sophisticated. The level of accuracy that is required should reflect the risk of inaccurate data. For example, a passenger might not trust the system in the future if it showed a bus was expected in a few minutes when in reality the bus had just passed. Passengers might be equally disappointed if Countdown showed that a bus had just passed when in reality it had not yet arrived. Inaccurate information may lead to negative perceptions of the system or even worse to incorrect travel decisions by passengers. To minimize these negative effects, accuracy levels need to be high.

The second finding suggests that ridership gains may not be as great as proponents initially envisioned them to be. One of the prime selling points of passenger information sys-

tems and AVL systems in general is the potential of these systems to increase ridership and therefore revenue so that they can pay for themselves in a relatively short time. This finding tells us that this may not be the case and perhaps these systems should not be judged strictly on a financial basis, but should also take social benefits into account.

The third finding is an interesting one because it appears to contradict the second finding. One might think that if a passenger values a system so much that he or she would be willing to pay a premium for passenger information, he or she should therefore be more likely to use a system that has passenger information more often than previously if the price of the service remained the same. This should have been reflected in increased revenue in the Countdown route, but unfortunately it doesn't appear to be.

One reason for this may be the questionable validity of the stated preference study used to determine willingness to pay. A stated preference study gathers data by presenting hypothetical choices and trade-offs, not real choices. In essence, the study asks how much passengers would be willing to pay for a service if it was implemented. Even with methods used to increase the robustness of this survey, this fundamental flaw remains. In addition, there may be some bias present since passengers may tend to overstate the system's worth intentionally in order to increase the chances of the system being implemented. Even if the survey was valid, there might be a fundamental difference between what a person states he or she is willing to pay and what a person is actually willing to pay.

4.5 Others

The three case studies described in this chapter illustrate the ways in which information technology is used, decisions are made and systems are implemented. These agencies are by no means the only ones to implement advanced computer and communications sys-

tems, however. In the United States, some agencies are implementing advanced technologies with financial support from the federal government. The knowledge and experience that is being gained from operational tests of these systems are being collected and synthesized under a federally sponsored program called the Advanced Public Transportation Systems program (APTS).

The mission of APTS is, “to enhance the ability of public transportation systems to satisfy customer needs and contribute to community goals by providing information on innovative applications of available Intelligent Vehicle Highway Systems (IVHS) technologies from a coordinated operational test and evaluation program” [APTS 5]. The program strives to carry out this mission by examining various IVHS-related technologies that can be applied to public transportation and then to evaluating selected technologies through operational tests currently being conducted in several US cities.

Many of these operational tests involve technologies that include both real-time passenger information and real-time operations monitoring and control functions. Some of these APTS projects along with related non-APTS projects and systems will be discussed briefly in this section which is broken down into agencies and systems that are primarily concerned with real-time passenger information versus the ones that are primarily concerned with real-time operations monitoring and control.

4.5.1 Operations Monitoring and Control Systems

The State of the Art, 1994 [57] lists 28 agencies in North America who have either implemented or are considering implementing an AVL system. Of these 28 agencies, about a quarter are using or planning to use GPS technologies, about half are using or planning to use signpost-odometer systems, and the rest are either using another technol-

ogy or have not yet selected a technology. Clearly, GPS and signpost-odometer systems are the two major competing choices in AVL technologies.

The three previous case studies have described systems using passive identification or signpost-odometer technology in sufficient detail to cover these technologies adequately. The focus in this section is thus on agencies which are implementing GPS systems as their primary source of location information which include most of the APTS operational tests of AVL systems.

Denver, Colorado

Denver is one of the cities that is conducting an operational test of its systems under the auspices of the APTS program. The Denver Regional Transportation District (RTD) is currently installing a GPS-based AVL system as part of an upgrade to its communications system, the main objective being to aid in operations monitoring and control. By providing location information and subsequently transmitting to a dispatch center, events such as off-schedule buses and emergencies can be detected and resolved quickly. Many of the objectives of this system are similar to the CIS system in Toronto even though the location technology is very different. The system utilizes an exception reporting strategy rather than a polling strategy in transmitting location information. This strategy identifies only off-schedule buses to dispatchers who are then charged with taking corrective actions. Processing on the bus compares schedules with actual locations to determine if a bus is off-schedule, and transmits to the dispatch center only when such a case occurs [5 and 57].

Locations of buses are shown in the dispatch center via map displays and the system has a silent alarm feature in the event of any on-bus emergency. As of February 1994, 208 out of RTD's fleet of 788 buses and 28 supervisor vehicles are in full operation under the AVL system and the entire system is scheduled to be fully operational shortly. Delays due to technical difficulties in implementing new GPS technology have caused the operational

test to start only recently. In the near future, once the AVL system is in place, RTD is planning to install a passenger information system that will include interactive displays.

Denver's AVL system is estimated to cost about \$10.4 million or about \$12,500 per bus, which is about the average cost of an AVL system (see Chapter 5).

Dallas, Texas

Dallas is another US city that is currently implementing a GPS-based AVL system as an APTS operational test which will be evaluated to determine general position accuracy and the system's overall effectiveness in controlling bus schedules. The evaluation plan is due to be part of a national evaluation plan that is to be applied to other cities with similar AVL systems in the US.

A major component of Dallas's AVL system is the Integrated Radio System which is comprised of 12 radio frequencies; three dedicated to data collection, one to tracking control and the rest (eight) dedicated to voice communication. Like Denver, an exception reporting strategy is used. The information gathered by the AVL system will be used for both real-time operations monitoring and control and for off-line analysis.

Service performance during any specified period will be documented and available for examination by transportation and division fleet managers. It is expected that this data collection will prove invaluable for vehicle and personnel management, fleet performance and scheduling. In addition to tracking vehicles with emergency conditions, the AVL system will also be able to track off-route vehicles, a feature that is not available in signpost-odometer systems. If a vehicle goes off-route, dispatchers will immediately be notified and corrective actions can then take place.

The system is not yet operational, with the software not yet working to specifications. Currently, 1200 of the 1300 buses in the agency's fleet are equipped with GPS receivers and the agency hopes to have the entire system operational shortly [5 and 57].

MBTA - Green Line AVI

Recently, the Massachusetts Bay Transit Authority (MBTA) has installed an Automatic Vehicle Identification (AVI) system on its Green Line light rail line and Fellows [30] recently analyzed the potential of this system. The AVI system consists of 33 wayside antennas located at key points along all Green Line routes. Encoders and transponders installed on all Green Line trains are able to transmit information about vehicle numbers, route numbers, the number of cars in the consist and the status of 4 alarms to a decision-maker at a central control location when a vehicle passes an antenna. In this configuration, train location is known only at discrete points (i.e. at every antenna). Fellows noted that although this configuration gave a lot more system-level information about Green Line trains in service, more information was needed in order to make really effective decisions.

Suggested elements for an effective control system included algorithms to calculate headway information, algorithms to match train location to scheduled data, graphical views of the system state and simulations running concurrently with operations to provide estimates of locations, headways and schedule adherence. Further simulations to forecast results of specific control actions would also provide a better basis for subsequent decision-making.

With the introduction of the AVI system, Fellows described a new potential control environment made possible with the information provided by the AVI system. System-wide information allows monitoring and control to be performed centrally, allowing decision-makers to know passage times of all trains at all detectors instead of relying on inspectors. The Green Line supervisors believe that this capability can ultimately lead to better control decisions by allowing decision-makers to detect problems more quickly and use the extra time to formulate strategies to intervene before it escalates into a larger problem. Deckoff's model estimated that AVI information could improve the percentage of

time that the short-turn decision is successful (success defined as a decision that results in a reduction of passenger delay) from 73.8% to 93.6%. Macchi estimated that express decision-making could be greatly improved given both predicted time savings and neighboring headway information, both of which are possible with the AVI system [73].

Fellows recognized that technology was not enough to improve operations monitoring and control, thus he suggested complementary steps such as ensuring continued expertise and teamwork, requiring field supervision experience for dispatchers and having common managers for inspectors and dispatchers

4.5.2 Passenger Information Systems

In addition to the AVL system projects, APTS is also engaged in the evaluation of several traveler information systems, most focussing on the integration of paratransit with conventional transit services. Passenger information systems can be categorized as systems providing pre-trip, en-route, or in-vehicle information, and selected APTS and non-APTS systems in each category are investigated below. A simulation that evaluated the impact of real-time information to a portion of the MBTA transit network is also presented in this section.

Pre-trip Information Systems

In Bellevue, Washington, the local transit agency is developing a pre-trip commuter information system that can be used to display information on transit, van and carpooling services. One of the goals of the Bellevue project is to examine ways in which mobile communications, such as cellular telephones and information kiosks can be used to make carpooling and vanpooling operations more attractive. The project initially developed a cellular-based ridematching service in order to increase usage of High-Occupancy Vehicle (HOV) facilities in the area. In the project's current phase, an interactive commuter infor-

mation center is being developed and installed in a downtown office building in Bellevue. In addition to providing computerized transit information and rideshare matching services, commuters can also schedule occasional carpool or vanpool trips. The system is also being developed to include voice mail, smart card, traffic monitoring and electronic map capabilities [5 and 57].

In Los Angeles, a smart traveler system is being developed with the aid of APTS that will provide pre-trip real-time information to passengers including transit system status and expected arrival times. This system is somewhat different from many of the other automated information systems in place in other cities (Ottawa, New York City, San Diego and Kitchener, Ontario) in that the information will be real-time instead of just scheduled. Information kiosks located at Union Station, Arco Plaza and a shopping mall will provide information of bus, light rail and heavy rail schedules and will also show maps displaying congestion on freeway and arterial roads [57].

En-Route Systems

An in-terminal component to Smart Traveler has also been developed in Los Angeles and information displays are currently installed on Amtrak station platforms. These displays primarily provide real-time transit arrival information and are currently updated from a central location. Unlike London Transport's Countdown system, however, it is the control center, not the vehicles themselves that trigger the information updates [57].

Teleride Sage, has developed several en-route information systems for cities in the US and Canada including OC Transpo's non-real-time 560 system and real-time systems in places such as Toronto, Guelph (Ontario), San Juan (Puerto Rico) and Broward County (Florida). The hardware for these en-route systems consist of screens inside the terminal that present material on arrivals, departures, detours, delays, cancellations and fares. The arrival and departure information is triggered by sensors that are located on the approach

to the station. The viewers are similar to the monitors in place at many airport terminals, but they provide more information and employ sharper graphics and resolution. It is also possible to carry advertisements and store promotions over the viewers [57].

Halifax (Nova Scotia) has a well-established real-time in-terminal system with displays located in transit terminals and malls that show real-time information on an interactive basis. When a traveler wishes to know the arrival time of the bus that he or she wishes to travel on, the traveler punches in a four-digit code that signifies their location. The display then takes this location information and displays real-time arrival information for all the buses that pass that location [57].

En-route passenger information systems are also well developed in Tokyo and Osaka, Japan. In Tokyo, the Bus Operations Management System provides both real-time operations monitoring and control and passenger information capabilities to the Green Line Series of buses operated by the Transportation Bureau of Tokyo Metropolitan Government. The passenger information system consists of panel displays at bus shelters and terminals that show a wide range of real-time information including bus departures, traffic conditions, bus locations (shown by points of light on map displays), current headways and a journey time indicator that predicts travel time from one stop to another [17, 50].

In Osaka, real-time bus information is provided at designated information spots and at selected bus shelters. At the information spots, passengers can obtain information such as fares and service via an interactive video linkup. Passengers can also call the service center to receive up-to-date information via telephone. At the bus shelters, map displays show the current location of arriving buses (down to the major bus stop level) and an imminent bus approach is signalled both by a chime and a lamp flicker [47].

In-Vehicle Systems

There are few real-time in-vehicle systems in operation with most of the development in the passenger information field focusing on either pre-trip or en-route information systems. Of the systems that do have some sort of in-vehicle component (Salem in Oregon, Orange, Osceola and Seminole Counties in Florida, JFK Airport in New York, Montreal in Quebec etc.[57]), the information that is given out is generally limited to next stop announcements, thus it might be argued that these systems might not be real-time in a meaningful sense. The primary motivation behind these systems is to design a system that conforms with the Americans with Disabilities (ADA) Act which requires transit to be accessible to all persons with disabilities, without requiring operators to be heavily involved.

MBTA - Passenger Information Simulation

Hickman [35] has explored the impact of real-time information on transit passenger behavior, developing a framework that models the ways that passengers alter their travel decisions in response to various types of real-time information. A transit service model that assumes stochastic vehicle running times, stochastic and time-dependent passenger departure times and path travel time distributions was initially developed as inputs to his travel behavior model along with traveler perceptions and types of real-time information available. Several scenarios were developed and investigated ranging from cases in which no real-time information was given to cases in which perfect information was provided to the passenger, and cases in which passengers underestimated variability of travel times to cases in which passengers overestimated the variability of travel times.

The outputs of the models included passenger path choice, departure time choice and resulting path flows and travel times. This model was first applied to a theoretical shuttle network and then to a section of the MBTA network stretching from Arlington Center to

Park St., including the Red Line and the 77, 79 and 350 bus routes. In both of these networks, several origin-destination paths were available to passengers, the travel times for each alternative path were in the same ranges and travel time reliability was considered to be an important issue. This represents ideal conditions for obtaining full benefits of real-time information.

Even with these carefully chosen networks however, the model forecast only modest time savings (about 1 - 3% of total travel time) as a result of real-time information. On a 30 minute trip, this translates to time savings of 0.3 to 0.9 minutes. As expected, some types of information proved to be more beneficial than others. An 0.5% savings was estimated for knowledge of departure times, while a 2% savings was estimated for running time information. Information on connections yielded even higher savings. In these scenarios, Hickman assumed a relatively high accuracy associated with the information, but after running a few scenarios where he varied accuracy levels, he found that travel time savings were fairly insensitive to accuracy levels.

Hickman's research concludes that real-time passenger information will probably not have a large impact on actual travel times. If a cost/benefit analysis was conducted purely based upon information costs versus travel time savings, these systems would probably be rejected. Information systems have the additional potential, however to provide emergency and service disruption information and little research has been conducted to evaluate the utility of these features. In addition, Hickman's models do not investigate the influence of real-time information on passenger's perceived waiting times and total trip times. The value of time savings may increase if perceptions are taken into account. In these contexts, real-time information may be more useful than Hickman's research suggests.

Chapter 5

A Framework for Selecting Technology Applications

5.1 Introduction

Thus far, this thesis has examined the information needed to support real-time public transportation operations control and passenger information functions and the advanced technologies and systems that can be used to gather and make use of this information. It has also introduced many of the issues that agencies must address when planning to apply information technology to their operations. These issues and the ways that agencies deal with them were then investigated through three case studies.

The ultimate goal of information technologies is simply to improve system performance, and design of technology application should thus begin with an assessment of the problems that the agency is facing. In some situations, information technology may be better applied to perform operations monitoring and control than using the same information for passenger information while the reverse may be true in other situations, and in still others, the situation may call for both applications, but in a specific order. When an agency decides upon technology, the first issue that must be decided is the most effective use for information technology to solve existing problems. The first section of this chapter describes situations where it may and may not be appropriate to implement information technology for real-time uses, either for operations monitoring and control and/or passenger information.

Once an agency decides on the use for technology, the agency must then select from a wide range of technologies and systems. Before detailed technical evaluations are conducted, however, the agency must define the general types of systems that they want. This

involves making choices on general issues that will greatly affect functionality, such as choosing between centralized and decentralized control, determining the mix of hardware, software and labor and choosing a discrete or continuous system. These issues are presented and evaluated in the next section.

After issues about general design are resolved, the agency needs to decide upon specific AVL system components which when integrated together, form a system designed to perform real-time functions. The final and most important evaluation that an agency has to make is the evaluation of the overall benefits and costs that result from the AVL system. The issues that pertained to specific component design were extensively described and evaluated in Chapter three, thus the main interest in this chapter is on the evaluation of the benefits and costs of these systems when applied to either operations monitoring and control or passenger information.

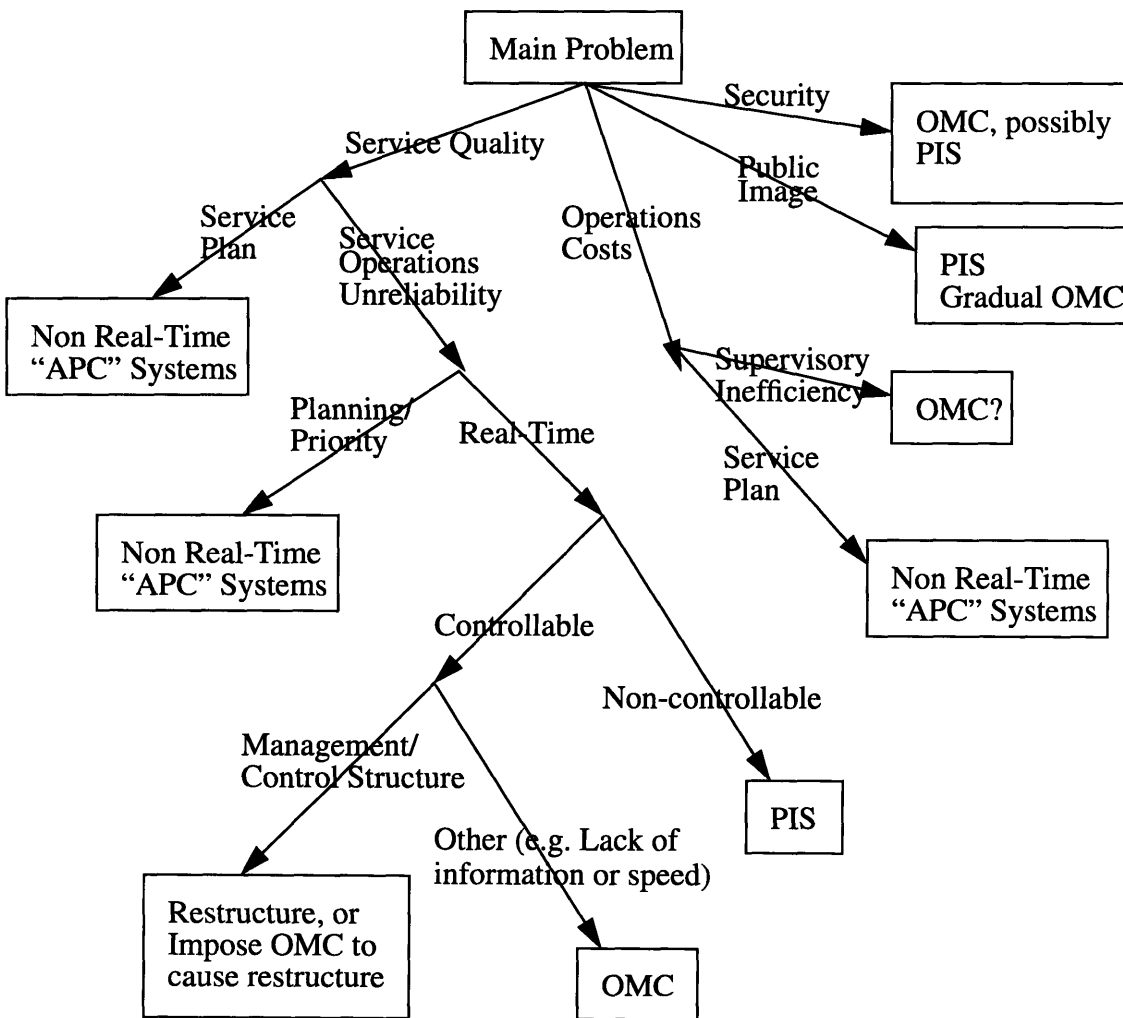
5.2 Appropriate Uses for Information Technology

The primary motivation for transit agencies implementing advanced technologies is an expectation that performance can be improved. In some sense then, only when problems occur in system performance does the need for using advanced technologies arise. The same applications of technology cannot be uniformly used to solve all problems, however, and before an agency selects a particular technology, it should first focus on matching their specific problems with the technology and use that is most likely to result in an effective solution.

Information technologies can only be effective in solving a limited number of performance-related problems, principally those related to service quality, operations costs, public perceptions and safety. A decision tree proposing the appropriate uses of information

technologies for each problem is shown in Figure 5.1 in which each branch of the tree represents a sub-classification of the problem. If an agency is suffering from any of the problems listed, the tree can be used to direct the agency to a potentially good use for information technology. If an agency is suffering from multiple problems, the tree can be useful in pointing out the combination of real-time uses which might be appropriate. Each of the problems displayed in the tree and the effectiveness of the uses for information technologies are described below.

Figure 5.1: Decision Tree for Application of Information Technologies¹



1. OMC = Operations Monitoring and Control, PIS = Passenger Information Systems

5.2.1 Service Quality

Service Plan

As described in chapter one, one of the primary concerns of any agency is collecting data and creating an efficient and effective service plan. The challenge is in creating a system that collects data in a systematic, frequent and reliable manner and then uses this data to assess existing services and to plan revisions effectively. Problems occur when a system fails in any one of these regards. Chapter 1 has already described how information technologies can be used “off-line” to improve the data collection function. It has also been shown that these applications can be very cost effective, as in the case of OC Transpo’s APC system. Information technologies (IT) used for OMC systems can also provide the tools necessary to collect good data, but the extra cost associated with OMC systems probably can not be justified if service planning is the agency’s only performance problem.

Service Operations Unreliability - Planning and Priority

If the service planning function is conducted efficiently and effectively, but problems exist with service operations, the potential exists for information technologies used for either operations monitoring and control or passenger information to be useful. The effectiveness of either function in solving operations problems depends upon the causes of the problem. Chapter 2 identified many potential causes of problems in bus operations and classified these problems as either planning/priority related or real-time.

Many operations problems that are planning/priority related can be most cost-effectively dealt with by an information technology utilized in a non real-time manner. Problems such as predictable traffic congestion or variations in passenger demand that recur systematically can be alleviated by adjustments to schedules and running times or by traffic engineering initiatives. These problems may also be alleviated by systematic real-time

intervention through operations monitoring and control, but the real-time aspect of this function is not necessary in this case and this would likely be a more expensive solution.

Service Operations Unreliability - Real-Time Uncontrollable

Other problems that occur in service operations occur in real-time and need real-time intervention in order to solve. Chapter 2 further classifies real-time problems into those with controllable versus uncontrollable causes. For uncontrollable real-time causes such as weather and unanticipated traffic accidents, operations monitoring and control can help, but can only be partially effective in alleviating the impacts on passengers. Operations monitoring can detect the problem, and information technology can accelerate this process, but these problems must be dealt with in a highly reactive manner, and the value of control intervention will depend on the circumstances. Service is already disrupted and passengers are inevitably affected, thus the objective of OMC becomes one of mitigating the impacts of the problem rather than solving it.

For the high costs that an OMC system requires, it may not always be the most cost effective approach in this context. One alternative is to use technology to support passenger information, which could relay information on service disruptions to passengers so that they are informed of the situation. Using this information, they could change their travel plans (the London Transport survey revealed that passengers would consider other travel options if they knew that their wait would be very long) or if they cannot, at least they know about their own situation. This would have the effect of lessening the impact on passengers.

Service Operations -Real-time Controllable

For controllable real-time causes of unreliability such as operator behavior and unanticipated fluctuations in demand, OMC systems can often be very effectively applied. These causes of unreliability are often relatively minor and reliability can be maintained

through the continual monitoring and control of the network. Agencies experiencing these types of reliability problems generally have inadequate OMC systems and the reasons for these deficiencies must be investigated before implementing a technological solution. If problems are rooted in the management or overall control structure, perhaps they can be resolved by changing management or the control structure without the need for new technology. OMC systems might however serve as a catalyst for structural changes and could be effective in causing beneficial managerial and control changes.

Other common inadequacies with current OMC systems are the lack of information gathered both locally and systemwide and the slowness of information transferred to decision-makers. Information technologies used for OMC could provide more systemwide and local information quicker to help improve the chances of making correct decisions, improving the impacts on passengers. By comparison, information technologies used for PIS would generally have less of an effect on passengers. First, no improvements to service reliability would be seen since information is being passed to the passenger rather than to decision makers who have the power to implement beneficial control measures. Second, although passenger information does tend to reduce the negative effects of unreliability, it is still clearly second best to the alternative solution of better reliability. Passengers would rather be able to depend upon reliable service than depend upon being notified of unreliable service.

5.2.2 Operations Costs

Sometimes performance problems are due to high costs of day-to-day operations. If the problem of high operations costs is caused by inefficiencies in the service plan, information technologies utilized in a non real-time manner may be the most effective solution.

Problems such as under-utilized vehicles and sub-optimal vehicle and crew scheduling can often be identified most simply through off-line analysis.

Sometimes, the problem is caused by inefficiencies in supervisory activities. For example, in 1991, the Massachusetts Bay Transit Authority's (MBTA) operator-to-supervisor ratio was much lower than the average of other comparable agencies [31,40]. Inefficiencies like these lead to high costs for supervision and overall management of operations. Information technologies used for operations monitoring and control can help to reduce these inefficiencies and thus reduce overall operations costs. In the TTC's case, vehicle-to-supervisor ratios increased as a result of CIS, but because of TTC policy, costs were not reduced. The potential exists to reduce operation costs, but political considerations that inevitably come into play when staff cuts are at issue may make real cost reductions difficult to realize. The TTC case study has also shown that OMC systems may be hard to justify solely on the basis of these cost savings.

Since real-time passenger information is a relatively new function in the transit industry it only adds to, rather than replaces, systems in place, thus no real cost savings can be realized by applying information technology to this function.

5.2.3 Public Perceptions

Public transportation has traditionally suffered from poor public perceptions when compared with alternative travel modes such as the automobile. Agencies can suffer from poor public perceptions if service is generally poor, but low public image may still exist even when service is good if competing modes provide higher quality service. Gradually, agencies are trying to turn around these perceptions by using information technologies to showcase their services, and using information technologies for real-time passenger information serves such a purpose. If agencies are having a problem with public perceptions,

and if their overall service performance is good, passenger information may be a good strategy since it is directly observable by the passengers therefore it may strengthen the image of the agency. A significant number of respondents to London Transport's survey had a better impression of London Transport as a result of the Countdown system.

This may be a better use for information technologies than operations monitoring and control. Although OMC equipment may be visible to most passengers, OMC systems work behind the scenes to improve service and thus image in a gradual fashion, but is not directly visible to passengers the way that passenger information systems are, and thus it is probably less effective at creating a positive public image. Also, if service reliability is initially good, OMC systems can only improve service by a small amount. Where OMC systems might be effective is when service quality is initially poor. By improving reliability, public satisfaction should steadily increase, perhaps leading to ridership increases and an increase in positive public perception. Reliability has been consistently shown to be one of the most important attribute of transit service to passengers [Levinson 40]. Although it doesn't have the immediate effects associated with passenger information, if reliability is initially poor, the effects of passenger information will gradually fade once passengers continue to observe poor service.

5.2.4 Security

Issues of safety may also play a large part in determining the appropriateness of technology. With congestion and crime worsening in many urban areas, agencies are becoming increasingly concerned about safety and security on transit vehicles. In the TTC's case, one of the prime objectives in developing CIS was to increase safety for both operators and passengers.

In terms of safety, information can be used effectively as part of the operations monitoring and control process. One of the primary functions of OMC is to monitor the network for any signs of trouble and then to react appropriately when situations occur. Information technologies aid the OMC function in relaying emergency information quickly to decision-makers so that situations can be quickly resolved.

This does not necessarily mean that passenger information does not increase safety, however. In times of emergencies, information like recommended procedures and safe exit routes can help passengers avoid danger. This type of information could be just as effectively provided by transit staff, however. Neither OMC nor PIS systems can probably be justified by the safety concern alone, but as passengers and operators become increasingly worried about safety, it is becoming a more important problem.

5.2.5 Combinations

Each node in the decision tree shown in Figure 5.1 applies mainly to appropriate applications of technology when only a single problem exists. In reality, this is rarely the case. Many of these problems are related to each other and the existence of one problem may indicate the existence of another one. For example, an agency that has a problem maintaining high service quality may also have a problem of poor public perceptions that is caused by unreliability. At other times, multiple problems may exist at an agency even if they are not related, thus an agency may have both a poor service plan and a security problem.

The solution of these multiple problems depends on their combinations and may call for joint uses for technology. In general, the more problems that can be effectively dealt with by a particular information technology system, the stronger the case for that specific use. For example, if an agency has both the problem of safety and of service reliability,

this combination strengthens the case for implementing information technologies for OMC use. These combinations are discussed below.

Service Plan Combinations

If the service plan and service delivery are both poor, it is probably best for the agency to focus on improving the service plan first before improving service delivery. This entails the implementation of an APC-like non real-time system before the implementation of a full-scale OMC system, or the implementation of an OMC system with extensive off-line data analysis capabilities. Operations control can be effective only when a good service plan is in effect. If the service plan is not effective, no amount of effort put into operations control can increase service to satisfactory levels. If the routes are poorly structured to begin with, even if service delivery is improved, it still will not serve the needs of the passengers. Not many passengers will use a route if it does not serve places they want visit. Only when the service plan is improved will the implementation of an OMC system yield the desired results.

The same argument also holds true for service plan and public perception problems. In this case, off-line applications should be implemented before real-time passenger information systems. If service is bad as a result of a poor service plan, passenger information systems can not be effective. Since the routes will not be serving the places where a majority of the riders wish to go, passengers will not be served even if passenger information is given. Only when the problem of the service plan is resolved will passenger information become effective.

If the service plan and safety are the problems, perhaps this combination would strengthen the argument for implementing an OMC system with off-line data analysis capabilities. The off-line systems would help improve the service plan and the OMC ele-

ments would help improve safety. An even stronger case for implementing OMC systems would come if the agency has the additional problem of service unreliability.

Real-Time Controllable Service Reliability Combinations

If an agency is experiencing poor service quality and poor public perceptions, perhaps both OMC and PIS applications of information technologies are justified. The OMC function could help improve service quality and indirectly help remedy perception problems and the PIS function would help remedy perception problems and would present the results of OMC directly to the passengers. This necessitates the implementation of the OMC function before PIS in order to be successful, however.

If the order of implementation were reversed, PIS systems would only be partially effective. Passengers regularly using bus routes that have unreliable service will already be aware of the type of service they are receiving. If a passenger information system was installed on these routes, service would still be unreliable, and the passenger would have the perception of unreliability reinforced, although the negative effects on the passengers would still be lessened because of passenger information.

If passenger information were installed after OMC, however, these systems would be more likely to complement each other. First, the system would highlight to the passengers how well served they are and second, passengers would be able to utilize their time more effectively. They would be able to arrive at a stop just minutes before a bus is scheduled to arrive with the confidence that it will indeed arrive on time. The passenger could then check with the PIS to make sure that, indeed, the bus will arrive on schedule. This reduces both the passengers' mean waiting time and their disutilities associated with waiting.

One needs to be concerned, however, that operations monitoring and control might decrease the value of passenger information like it has on the Riverbus system. If reliability can be made near perfect, as is the case on the Riverbus system, there would be little

added value if a PIS system were added. The best situation for implementing both OMC and PIS functions may be one where a network is unreliable, and operations monitoring and control can improve reliability, but only to a certain point, after which the remaining unreliability can be dealt with by the passenger information system. Since this situation can occur frequently in large transit systems, the potential to utilize information technologies for multiple functions can be high.

If an agency experiences problems encompassing both service quality and safety, this strengthens the case for implementing OMC. Not only does the OMC function have the potential for improving service reliability, it also has the potential to improve safety. PIS systems used in conjunction with OMC may also be effective in this problem combination in improving safety, but it may not be worth the cost to provide incremental benefits in safety. The case for OMC systems is also strengthened if both reliability and operations costs problems exist since the OMC function can help solve both problems.

Real-Time Non-Controllable Reliability Combinations

If an agency is experiencing reliability problems that OMC cannot fully remediate and also has public perception problems, this further strengthens the case for passenger information systems. Reliability problems that cannot be dealt with effectively by operations monitoring and control can be better dealt with by providing passengers with real-time information. At the same time, this information helps improve the agency's image.

5.3 AVL General Design Issues

Once an agency decides on the appropriate use for technology (if any), it must examine certain AVL technological issues that will have a fundamental impact on the best system design. These issues are discussed next.

5.3.1 Centralized vs. Decentralized Systems

This issue focuses on how technology, monitoring and control responsibilities should be distributed in the system. Until now, this thesis has assumed a centralized system with most of the data processing technology and decision-making at a central location. An alternate configuration is to decentralize parts of these components to the vehicles or other field locations. For example, instead of having one large central processor performing all of the processing, storage and interfacing, much of the processing, storage and interfacing could be performed on the vehicle itself. Also, instead of having central controllers monitor the system at a detailed level, each vehicle could monitor its own performance and alerts the operator when appropriate, or the controller only in serious situations.

Decentralization should reduce the amount of communications required between vehicles and central control. Normally, data would be sent over wireless communications and the computer at central control would process this data. In a more decentralized system, much of this data would not be sent to central control, rather it would be processed directly on the vehicle. This would require more sophisticated and powerful hardware and software on vehicles to handle the processing needs and store the required data.

In a centralized system, the hardware and software on the vehicle is only responsible for controlling the flow of data to and from the vehicle and perhaps providing the operators with a simple interface. In a more decentralized system, the hardware and software would be required to do more things, such as converting location data into something more useful like schedule deviations, storing some data for post-processing, or providing an enhanced user interface to show any additional processed information. In each of these cases, hardware and/or software needs on the vehicle would increase: schedule data for the vehicle's daily run would be needed for schedule adherence information, extra memory

would be needed to store more data, and more hardware and a bigger display would be needed for the enhanced interface.

The issue of decentralization goes beyond hardware and software, however, also raising the issue of who should have decision-making responsibility: the operator or the central controller. Local decisions made by the operator may be effective when relatively small incidents occur on the field or when the vehicle is on a low frequency route, but centralized decision-making made by the controller is necessary either to resolve major incidents or to control vehicles on high frequency routes. Also, local information may be sufficient if control actions affect only a single vehicle while system-wide information is necessary if control actions will affect multiple vehicles.

A partially decentralized system that provides limited communications with central control and retains controllers for monitoring and decision-making, but keeps most of the hardware, software and processing on the bus may create the ideal system configuration. Many of the Smartbus systems being planned in the United States provide this type of structure: a majority of the processing and some of the control decision-making being done on the bus and some communications take place between the bus and a central control location. Operators are continually notified of vehicle status so they can make frequent, minor control changes, and controllers are notified only in cases of major disruptions or whenever the controller specifically requests information. This configuration may present the best control environment while at the same time minimizing communication requirements.

In terms of costs, it isn't clear that a partially decentralized system would cost less. There would be less need for a complex communications system, nor would there be a need for such a powerful central processor. All of these factors would reduce costs. Costs would increase, however, from the need for more sophisticated equipment on the buses,

and the controller costs would still be present. The sum of the costs of the equipment and software onboard vehicles might actually be more than the cost of equivalent central equipment and software because of the duplication which may be necessary in equipment, software and processing.

The partially decentralized system described above might be preferable to a fully centralized system because it might lead to better decision-making by using both local and system-wide information, and would lessen the demand for data communications between the bus and central control. This type of system may be more expensive, however.

5.3.2 Hardware - Software - Labor Substitutions

In the previous discussion in Chapter 3 about technology and human factors, many examples of how hardware, software and labor can substitute for each other were mentioned. Decision-making software has the potential to substitute (at least partially) for controllers and other decision-makers. Map matching techniques for location data can substitute for the need for more advanced equipment to produce more accurate location estimates.

These are but a few of the many ways that hardware, software and labor can be interchanged within a system design. Chapter 2 described a variety of information needs and uses for real-time decision-making. The motivation for substituting components in the system design is that by so doing, information needs can be met at lesser cost or at a higher level of performance. Given a certain combination of technology and labor, the theory is that if an agency wishes to maintain the same level of performance, it can decrease labor by a lot if they increase technology by a little. The result would be a cost reduction since the decrease in labor costs would more than offset the increase in technology costs.

Technology can substitute for human labor in many instances. It is possible to replace some inspectors with AVL systems just as it is possible to replace some controllers with

automated decision-making systems. In the extreme, it would even be possible to substitute operators with automated vehicle control systems.

The type of substitutability that occurs between technology and labor can also apply between hardware and software. Software can usefully be substituted for hardware if it can lead to either reduced costs or improved performance. In many circumstances, when a certain system is installed, the hardware costs turn out to be a lot more than the software costs. The main reason for this is that hardware costs vary directly with the number of buses that are equipped, while software costs are largely independent of the number of buses. The same software can be loaded onto any number of buses at much the same cost. It can be seen that there are advantages in substituting software for hardware, especially for large transit systems.

Another motivation for substituting software for hardware comes from the notion that software can last longer than hardware. With technology changing so rapidly, hardware may become obsolete in a relatively short amount of time. Not long ago, the TTC was an innovator with its CIS system using signpost-odometer technology, but by today's standards, their location technology might be considered obsolete with the rapid development of GPS technologies. Software, however, tends to last longer. If software is programmed efficiently and takes future needs into account, it can be applied to several generations of hardware. This is the case with OC Transpo's APC system. The hardware for its APC has changed several times, but its software that process data has simply evolved since APC was first implemented.

Software can substitute for hardware in a variety of ways. It has already been illustrated how map-matching software can increase locational accuracy. Consider a system that already uses dead-reckoning techniques, but wants to obtain better accuracy. They have their choice of either signposts or map-matching, and let us assume that they can

both increase accuracy by the same amount. The larger the transit agency, the more advantageous it would be to use map-matching since signpost costs increase as network size increases, but map-matching costs remain relatively constant. Error-correcting algorithms are another way that software can substitute for hardware. These algorithms can increase accuracy and can substitute for a more expensive but more accurate location technology. A final example is prediction algorithms similar to the ones used at London Transport. Algorithms that predict the location of a bus a short time in the future may be able to substitute for a denser network of signposts, resulting in lower costs and a small loss in accuracy.

Not all software substitutions are limited to location accuracy. Software substitution can also occur in central control. Software concepts like virtual memory can “fool” the computer into thinking that there is more memory than there actually is, thus reducing memory costs. More efficient programming can increase the speed of the computers, thus in the end you may need less computing power. These are but a few examples of substitutions in the control room.

Agencies have flexibility when determining the mix of labor, hardware and software inputs to meet their information needs. From the previous discussions about information technologies and from lessons learned from the case studies, several points can be made about relative costs of labor, software and hardware in the specific context of AVL systems:

Hardware

For the past several decades, hardware has been becoming less expensive. The unit costs for speed and storage has steadily been decreasing and although hardware costs still make up a significant proportion of total AVL system costs, its share has been decreasing

over time. Hardware needs to be installed in every vehicle, however, which makes hardware costs a function of fleet size.

Software

Innovations in programming tools and aids which help programmers achieve results in a shorter period of time have resulted in decreases in software programming costs. Offsetting this however, are increasing costs of programmers wages. Like any other agency or vendor employee, programmer wages are subject to inflation and increase over time, thus the net impact on expense over time is unclear. Software costs are relatively invariant with fleet size, however.

Labor

Labor costs have definitely been increasing over time and also vary directly with fleet size.

Given the cost structure of hardware, software and labor, one can imagine certain scenarios where a particular distribution of hardware, software or labor is preferable.

In transit agencies with relatively small fleet sizes (less than 100 buses) it may not be cost effective to substitute either hardware or software for labor. These agencies usually operate in smaller cities and encounter fewer problems in terms of maintaining safety and reliability. Many times, all that is needed for good control is relatively simple manual supervision. With small fleet sizes and few routes, frequencies are unlikely to be high, thus reliability can usually be maintained relatively easily. Unless an AVL project is initiated for demonstration purposes, AVL systems might not be appropriate. The fixed costs of hardware and software needed for AVL systems might not be justified by the cost savings in labor and benefits to real-time operations that these systems could provide.

In medium-sized transit networks with medium fleet sizes (100 to 500 buses), AVL systems may be cost-effective, and the optimal AVL configuration may be hardware-intensive. For a medium-sized agency problems of service reliability and safety are likely to occur which cannot be solved by relying exclusively on manual monitoring and control methods. If AVL technology is going to be applied to only a moderately sized fleet, the hardware costs may be relatively low. Software can be programmed to replace hardware, but for these agencies, it might not be cost effective to perform this substitution because the costs involved in software development may outweigh the savings involved on vehicles and in the field. The situation may be a little different if an already-developed software package can be applied easily. If this is the case, then it might become cost effective to replace hardware with software.

Where software substitution for hardware might be most appropriate would be in large transit systems. For these agencies, the problems of safety and unreliability are likely to be acute and almost impossible to manage by relying strictly on manual control systems, thus some form of AVL system will likely be cost-effective. For these AVL systems, since software costs are relatively independent of fleet size, software replacement for hardware might make sense. Of course more effort would be needed to program larger systems but the same is true for hardware, as required capacity and storage increases. But if software can be substituted for some of the hardware on the vehicles, the added software cost would be distributed among the vehicles and the resulting cost per vehicle could be less than the hardware it replaced. It may also be cost effective to replace labor with hardware and software in large systems.

The issue should not be limited strictly on the basis of the costs above, however. In addition to considering the annualized cost (software and programming are more like one time front end costs as opposed to labor and maintenance which are ongoing costs), higher

levels of efficiency, reliability and effectiveness may be achieved by making appropriate substitutions.

Independent of system size, other issues that may influence levels of substitution are transferability and rate of change. Systems need to be designed such that components designed for one system are easily adaptable to other systems when an agency wishes to integrate components together. Also, components may become obsolete over periods of time and will need to be upgraded, and systems need to be designed to anticipate upgrade needs. Generally, hardware is the top of the list in both issues since it is mostly hardware that is changed or altered during integration and it is also hardware that becomes obsolete at the fastest rate. To minimize the costs of integration and upgrading, components need to be designed in the modular manner as discussed in Chapter 3. To further reduce these costs, software substitutions might be used since software becomes obsolete at a slower rate than hardware and thus needs to be upgraded less often.

Table 5.1 shows hardware-software-labor trade-offs for different sized systems by depicting systems that are labor, hardware or software intensive and their relative implementation costs to provide similar levels of service performance.

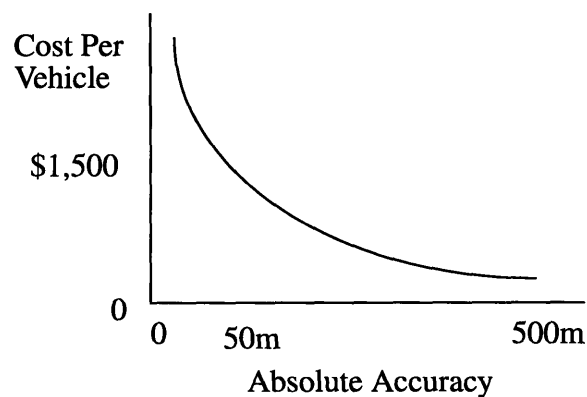
	Small Systems		Medium Systems		Large Systems	
	Per Vehicle Basis	Annual Basis	Per Vehicle Basis	Annual Basis	Per Vehicle Basis	Annual Basis
Hardware	High	High	Medium	Medium	Medium	Medium
Software	Very High	High	High	Medium	Low	Low
Labor	Low	Low	Medium	High	High	Very High

Table 5.1: Relative Hardware, Software and Labor Costs for Different Sized Systems

5.3.3 Cost vs. Accuracy

In order for AVL systems to operate effectively, accurate bus locations are essential. Locations that are inaccurate can lead to errors in control decisions and errors in the real-time information given to passengers. Accuracy requires more investment, however, and there is a direct relationship between the two as shown in Figure 3.6 (Hamilton [34]). This graph implies that with inaccurate systems, a small amount of extra investment can increase accuracy dramatically up to a limiting point. After that point, it takes large investments to obtain small increases in accuracy.

Figure 5.2: Cost vs. Accuracy of AVL Technologies¹



One must also think about what an acceptable accuracy is, in system terms. Clearly an upper bound on accuracy is a bus length of about 40 feet (or 12 meters) since it is meaningless to attempt to locate buses with any greater precision. Beyond this, one must look at what the data is being used for and what the implications of errors may be on performance.

For both operations monitoring and control and passenger information, accuracy does not appear to be too critical. Suppose that an agency was able to tolerate 15 seconds of location inaccuracy on a relatively high frequency route (i.e. for a given estimated loca-

1. Source: Hamilton [32]

tion, the vehicle is actually within 15 seconds downstream or upstream of that point). If a bus travels at a mean running speed of about 15 kilometers/hour (about 10 miles/hour), then the required positional accuracy would be about 60 meters. Increasing accuracy past this point may not be cost effective since control decisions are not likely to change if the system were more accurate. This is also true for passenger information systems since passengers will probably not notice an inaccuracy of 15 seconds.

Accuracy at this level only becomes an issue if the accuracy is incompatible with the software. For instance, some software that puts these locations into finely digitized maps in real-time might have difficulty with inaccurate locations. Inaccuracies of 60 meters might incorrectly place buses in the middle of buildings or parks when they really should be on the streets. For these systems, more accurate locations may be needed.

Radio-navigation technologies such as GPS and LORAN-C now have the ability to provide such accuracies at a relatively low cost, thus they establish a standard for the issue of accuracy. For older technologies such as signpost-odometers, the issue of accuracy is a little bit different since accuracy is exact at each signpost but errors increase until the next signpost is reached. For these systems, if an odometer was accurate to +/- 5% of distance traveled, and if signposts were placed at every 1.5 kilometers (about the level of spacing used in Ottawa, Toronto and London), theoretically the maximum error would be 75 meters and the average error would be about 40 meters which would still be within the accuracy required for effective use of information. This location information is not useful, however, if it is not available to decision-makers on a frequent basis, which raises the issue of acceptable update frequency, presented next.

5.3.4 Discrete vs. Quasi-Continuous Location

Related to the issue of accuracy is that of location update frequency. Some systems update bus locations on a frequent basis by polling; for example, the TTC and LT update locations every 20-40 seconds. This is an example of a quasi-continuous system. Discrete systems update locations infrequently and can include systems that poll infrequently, or that rely exclusively on signposts. Quasi-continuous systems are definitely more accurate in that they update more frequently.

A question that must be asked is if the extra cost needed for increased update frequency is justified. Increased polling rates necessarily leads to increased channel requirements. This may mean paying for more channels or paying for technologies to increase channel capacity. With a technology such as passive identification, wireless communication is not even required if the agency only wishes to locate vehicles to the nearest signpost.

Extra costs are also incurred at the central control computer which has to process more data at a faster rate. Controllers also have to deal with more information, but with the right user interfaces, these effects could be minimal. Saracino [56] defined order of magnitude costs for four different types of location systems used in different ways. The costs originally estimated in French francs, are converted to US dollars and are shown in Table 5.2.

While these cost figures are high (due to the fact that the estimate was done in 1988), the table does suggest that the costs of a system that providing continuous location can be more than double the costs of a system providing discrete locations, which may be reasonable since discrete systems can avoid any wireless communications costs. In their interpretation, discrete systems were judged to be only signposts which transmitted data to central control via wire links while quasi-continuous systems were radio linked buses with poll-

ing. The challenge then thus becomes first choosing between a discrete wire-based system and a radio-linked quasi-continuous system and then determining acceptable levels of update frequency.

	Real-time data transmission	No real-time data transmission
Quasi-Continuous Location	\$13000 to \$20000 / bus	\$9000 to \$18000 / bus
Discrete location	\$4000 to \$11000 / bus	\$3000 to \$9000 for signposts \$400 to \$2000 / bus equipment and software

Table 5.2: Relative Costs of Quasi-Continuous vs. Discrete Systems

Radio-linked polling systems are generally more expensive than discrete systems and require much more communications, but once the initial infrastructure is in place, update frequency can be increased easily by reducing the polling cycle. To increase update frequencies on discrete systems, new signposts and lines need to be added, which may be costly.

To determine what an acceptable information update frequency might be, one must return to the issue of the uses for the location information. For operations monitoring and control, the update frequency requirement is likely to be related to the headway of a route. For a long headway service, the update frequency can be lower than for a short headway service. For example, 5 minute updates may be acceptable for routes of headways 15 minutes or more, but would be wholly unacceptable for routes with headways of 10 minutes or less. In the 5 minutes between updates, the vehicle could have slowed down, stopped or sped up, and given the high variability of running time over short distances, this could mean several minutes of uncertainty which could jeopardize effective control on high frequency routes or for passenger information in general.

For comparison purposes, a system based only on signposts every 1.5 kilometers would receive information about every 6 minutes if a 15 kilometer/hour average bus speed is assumed. If this system is to be used on a network offering only long headway service, such a low frequency of updating may be appropriate, but more continuous updating through either prediction algorithms or through combining location technologies is needed if short headway services are also offered.

A system needs to be designed that can either provide an adequate update frequency for each route, (the AVL/C case study for OC Transpo is an example of this), or has the capability to provide more or less continuous information that is appropriate for all levels of service, which is the case at the TTC. It can be seen that an update period of about 20-40 seconds satisfies all types of headways, but places heavy demands on bandwidth capacity.

5.4 Operations Monitoring and Control Benefits

In this section and in the next one, the impact of the information that is being provided by AVL systems on the decision-making capabilities will be discussed. As in chapter two, two primary uses of information are investigated: operations monitoring and control and passenger information. Chapter 2 illustrated how advanced technologies can provide better information and this section discusses the benefits which should result.

Schedule Adherence

One of the purported benefits of AVL systems is the ability to improve schedule adherence. From the case study of the TTC and OC Transpo, it seems likely that AVL systems can indeed help agencies provide better schedule adherence. Phase VI analysis of CIS routes at Wilson Garage supports this quantitatively and comments from managers and

inspectors supports it qualitatively. Sufficient analysis has not been performed however, to answer definitively the question of the size of the effects of AVL systems on schedule adherence. It is known that AVL systems probably improve schedule adherence, but it is still unclear how much they improve it. Indeed the size of the impact will certainly depend on operational and management practices as well as the specifics of the AVL system itself.

Safety and Security

Another reported benefit of AVL systems to operations monitoring and control is increased safety and security. The fact that AVL systems provide constant vehicle monitoring capabilities and opportunities for operator reporting gives enough reason to believe that AVL systems enable agencies to handle incidents better and to provide more safety and security. AVL systems also decrease the response time to vehicle emergencies. The TTC has determined that the average response time for an emergency reported via a vehicle alarm is about 2-3 minutes¹, which is much faster than the time required before CIS was implemented.

Supervisory Efficiency

Another reported benefit of AVL systems is the ability it gives to agencies to allocate its control room and inspector staff more efficiently by increasing supervisor effectiveness without reducing staff or reducing staff without decreasing supervisor effectiveness. Theoretically, AVL systems tend to increase the efficiency of supervision (i.e. more operators or vehicles can be controlled using fewer supervisors) with all other factors remaining equal and the TTC analysis seems to support this notion. There is no evidence, however, that supports the notion that AVL systems actually reduce supervision costs.

1. Statistic gathered from interview with Dave Taylor, MIS Manager, CIS Project, TTC

Working Environment

AVL systems purport to make supervisors more comfortable by taking them out of the outside environment and putting them into a more comfortable inside environment. AVL systems also purport to improve operator working environment by making their vehicles more safe and secure. From surveys and informal interviews with inspectors at both the TTC and at OC Transpo, a mixed view emerges of the changes to the working environment. Most agree that AVL systems cause a higher level of stress due to the increased information that is presented to the decision-maker and the requirement for more and faster decisions. Many inspectors are indifferent to the changes in their physical environment. Some like the fact that they are indoors now and protected from the elements but others miss the interaction with the public and the operators that field work had afforded them. In a survey conducted by the TTC, 61% of all operators believed that the greatest benefit that the CIS system has provided to their working environment has been the CIS radio, which provides safety and security and increased communications benefits.

Non Real-Time Benefits

There are some benefits such as increases in ridership and vehicle utilization that do not occur in a real-time sense. Since this thesis focuses on real-time benefits, these benefits are not discussed in detail, but since these benefits are potentially important ones, they are worth a mention here.

Using a comparative ridership analysis conducted between different garages, the TTC's CIS evaluation projected a \$2.8 million increase in revenue due to ridership increases, which makes up a large percentage of the monetary benefits. As discussed previously in Chapter 4, however, these results are suspect. In reality, AVL system effects on ridership are not known with any certainty and further analysis utilizing better methods needs to be conducted to shed more light on this benefit.

One of the greatest reported non real-time benefits of AVL systems is the ability of these systems to gather better data on certain measures such as running and dwell times and layover times which can influence schedules. The ultimate result may be more effective utilization of vehicles which would mean that less vehicles would be needed to provide the same level of service. The TTC analyzed vehicle utilization changes in its Phase VI Final Report and found that CIS-equipped routes required between 4.3% and 9.2% less vehicles than non CIS-equipped routes, but one should be wary of these results because of the analysis techniques used.

5.5 Passenger Information Systems Benefits

Passenger Behavior

A purported benefit of passenger information systems is the positive influence these systems have on passenger behavior in general and the disutility of transit trips specifically. With the aid of information systems, it is possible for passengers to make better decisions about their trips and thus save time and stress. These information systems can lessen the disutility and stress normally associated with waiting for vehicles to arrive by displaying estimated arrival times. This way, passenger can spend less time waiting and more time in other activities without the worry and impatience that waiting causes. Hickman's [35] analysis, however, suggests that total travel time savings may be relatively small (on the order of 1 to 3 minutes savings) and London Transport's survey analysis [59] estimated only a 0.5 to 1 minute reduction in perceived wait times.

Reliability

In most cases, a system that exclusively provides passenger information and no operations control will not appear to increase reliability. One might argue however that opera-

tors will try harder to adhere to schedule once they realize that passengers will have improved information and thus have improved knowledge of service levels. This conjecture has not been proven, however, and should be assessed in the same manner that normal schedule adherence is assessed.

Passenger Valuation

In the London Transport study, results indicated that passengers are willing to pay almost a quarter of their entire fare as a premium in order to receive real-time information. The study also showed the potential danger in using stated preference data directly as the same data was used to estimate ridership increases of about 12% which simply did not materialize in reality.

Passenger Perceptions and Attitudes

In the field of market research, perceptions and attitudes are very important in determining benefits of potential new products. Knowledge of perceptions and attitudes provide similar importance in evaluating passenger information systems. London Transport directly surveyed passengers and asked them whether the Countdown system improved, worsened or did not change passenger attitudes towards bus travel, bus operators and London Transport in general and the level of support for information systems. In the London Transport study, a significant percentage of passengers had a positive perception of Countdown and many stated that this changed their attitudes towards transit in general and London Transport in particular.

Ridership

London Transport measured ridership on similar routes, one (route 18) having the Countdown system and the others not having Countdown. They found to their disappointment that there was no significant increase in ridership due to the information system.

5.6 Costs

Cost is one of the most important aspects of new technology and most of the decisions that are made about system size, features and capabilities and system utilization have cost as a primary input. For agencies that are considering AVL systems, the cost elements of greatest concern will be capital and start up costs. The sources of this cost data will usually come from software and hardware vendor quotes and/or from internal or external consulting estimates, all of which will be imperfect.

Table 5.3 shows estimated per vehicle costs for some agencies in North America for which costs have been reported. Of all these systems chosen, only one agency is included that utilizes GPS; the rest use signpost-odometer technology. It is shown here that typical per vehicle costs for larger-sized systems average around \$11,000 to \$13,000 while per/vehicle costs for smaller system costs are somewhat lower.

City, State/Province	\$M	Location	\$/ Vehicle
Denver, CO	10.4	GPS	\$12,500
Fort Lauderdale, FL	2.3	SO	\$12,000
Halifax, Nova Scotia	1.0	SO	\$5,900
Kansas City, MO	2.1	SO	\$7,600
Norfolk, VA	2.0	SO	\$12,500
Ottawa, Ont.	N/A	GPS, Signposts	\$7,300 - \$11,000
San Antonio, TX	3.7	SO	\$6,900
Seattle, WA	17.0	SO	\$12,700
Tampa, FL	1.6	SO	\$9,300
Toronto, Ont.	37.4	SO	\$12,000

Table 5.3: North American AVL Systems^a

a. Source: State of the Art, Update, 1994

In a recent study, Morlok[45] suggested a cost model based on annualized total investments and annual operating and maintenance costs, but there are many different types of costs that are required for an AVL system and disaggregation of both investment and operating and maintenance costs might be appropriate. In general, AVL system costs can be broken into several categories which are discussed below.

5.6.1 Development Costs

Before a final system is selected, an agency may have experimented with several systems and the costs associated with experimentation and development have the potential to make up a significant portion of total costs. Development costs include costs for prototypes, for limited AVL trials, for software and hardware development and even costs for previous evaluations. Agencies can partially avoid these costs if they choose a technology and system that is already developed and well tested.

As the TTC case study shows, if the agency starts from scratch, then they can expect to spend a lot of resources on system development since they will be encountering both problems that no agency has researched before and problems that arise specific to the agency and locality. If a system has already been developed and is simply tailored to a specific agency, development costs will likely be a smaller proportion of total costs. All of the problems of the system have supposedly already been solved and all that is left is to solve problems that arise specific to the agency and locality. The consulting and equipment cost may be high, however, since the original system developers need to recover their development costs and wish to make a profit on their systems, while there is no such objective for in-house developers. Development costs can make up from 25 to 40% of overall costs of system-wide AVL installation and operation.

5.6.2 Capital Costs

Once the development is completed and a final system is chosen, it will be implemented on the network, generally on a systemwide basis. This implementation incurs specific start-up capital costs, which can make up between 35% to 65% of overall costs. A further breakdown of capital costs is given below:

Vehicle Costs

Even in a system that has significant central control capabilities, vehicle costs will likely make up a significant proportion of all costs. These costs vary directly with the number of vehicles that are AVL equipped. Among the costs that are associated with vehicle costs are hardware, software and installation costs. Vehicle costs can total as little as 5% of overall costs and as much as 25% of overall costs, and about 20 - 70% of all capital costs. Generally, the more decentralized the system, the higher the vehicle costs.

Control Center Costs

Many types of costs encountered in the control center are similar to the ones encountered in the vehicle. In general, for each cost type, costs are likely to be much higher at the control center than for any individual vehicle, but when the costs are distributed on a per vehicle basis, they tend to be less than vehicle-based costs. Usually, control center costs make up a small percentage of both overall costs (1 - 20%) and capital costs (5 - 40%). The more centralized the system, the higher the control center costs.

Field Costs

Field costs are costs associated with the infrastructure required in the field to aid in communications and/or location. These would include such things as roadside beacons and signposts, node antennas and passenger information displays. This cost type also varies with system size as reflected in system coverage rather than number of vehicles. At

larger fleet size, network size will increase which will increase field equipment costs. For OMC systems, these costs are relatively low, contributing a negligible amount to overall costs, while for PIS systems, these costs can be significant, contributing up to 20% of overall costs and up to 70% of all capital costs.

5.6.3 Operating Costs

Once a system is fully operational, the system will incur costs on an annual basis for maintenance and daily operations. Supervisory staff, managers, analysts and programmers will need to be paid for their duties and from time to time, equipment and software will need to be replaced or modified. These costs can make up a large part of overall costs since unlike capital costs which are only one-time costs, these costs occur year after year. These costs amount to between 10 - 40% of overall costs.

5.6.4 Example Cost Breakdowns

Taking data primarily from the TTC's Phase VI analysis of CIS at the Wilson Garage, proportions of costs are estimated and allocated to each cost category and cost type in Table 5.4. These percentages are based upon a total cost of about \$4.7 million by combining hardware, software, installation, operations labor and prior development costs that were estimated separately in the Phase VI Final Report.

As the CIS system was expanded systemwide, the development costs declined as a proportion of total costs. It is clear to see in this example that an agency can avoid a substantial cost if it chooses an established system that does not need very much extra development or customization.

Cost Type	Development Costs	Field Costs	Vehicle Costs	Control Center Costs
Hardware Costs	~37%(\$1.8 million)	~1%(\$47,000)	~18%(\$850,000)	~3%(\$150,000)
Software Costs ^a		negligible	~4%(\$190,000)	~9%(\$427,000)
Installation Costs ^b		~2%(\$95,000)	~6%(\$285,000)	~3%(\$150,000)
Operation Costs ^c		~15%(\$750,000)		

Table 5.4: Allocation of Costs for TTC's CIS Phase VI^d

a. Here it is assumed that programming for central control makes up about 70% of the total programming effort and the rest is software for the vehicles.

b. Here it is assumed that installations on vehicles makes up about 50% of the total installation effort and field installations make up about 20%.

c. Operations costs are derived from system estimates of operations costs of \$1.6 million/year factored down to Wilson's size (about 10% of the entire fleet), thus the cost was estimated to be about \$150,000 per year for 5 years with no interest rate, thus a total cost of \$750,000.

d. Source: TTC [26] and M.M. Dillon [25]

Another cost breakdown of an AVL system comes from London Transport's description of the Nag's Head Expansion Scheme and is presented in Table 5.5. In this table, total costs for Countdown were estimated to be about \$7.2 million if annual operating costs and development costs are also included.

Cost Type	Development Costs ^a	Field Costs ^b	Vehicle Costs	Control Center Costs
Hardware Costs	~36%(\$2.6 million)	~18%(\$1.3 million)	~8%(\$540,000)	~1%(\$90,000)
Software Costs				
Installation Costs		Included in Hardware and Software Costs		
Operation Costs ^c		~38%(\$2.7 million)		

Table 5.5: Allocation of Costs for London Transport's Nag's Head Scheme^d

a. The costs of the Route 18 test of \$2.1 million are added to development costs of \$75,000. Also added are \$440,000 in miscellaneous and project management costs.

b. Does not include bus shelter construction costs

c. Operations costs are assumed to be \$540,000/yr or \$2.7 million for a 5 year horizon

d. Source: Director of Planning [30]

In London Transport's example, the major costs shift away from the vehicle and the control center and into the field. This is due to the high infrastructure cost involved in installing passenger information displays on a large number of bus stops. There is also high costs due to operations and maintenance possibly due to a conservative estimate.

If an agency wishes to evaluate the costs of a proposed system, this type of breakdown might be useful. It is helpful to segregate vehicle costs from control center costs since vehicle costs can be used as a proxy for the variable costs of any proposed system and control center costs can be used as a proxy for the fixed costs. It is also useful to segregate hardware, software and installation costs since both hardware and installation costs vary with fleet size while software costs are more invariant. Sometimes, however, it is not possible to segment these costs in such a fine manner.

Cost estimates can be presented in different ways. The presentation shown here is in the form of total costs which gives the big picture. If possible, cost should also be presented on a per-vehicle basis, segmented by the different cost types. In this form, agencies will be aware of incremental costs of the system should the agency decide to increase or decrease their fleet size. The presentation shown here also only shows costs in terms of present costs, which is useful for agencies who wish to purchase systems outright, or are interested in knowing the one-time effect of this cost on their capital budgets. These costs can also be annualized for agencies who are interested in determining the annual effect of a proposed system to their annual budgets, or who are interested in leasing the AVL system over a certain period of time.

5.6.5 Costs for Incremental Functionality

It may also be useful to determine costs from a standpoint of functionality. For example an agency that already has a basic AVL system with some operations monitoring and

control functionality (provided as a result of the AVL system) may wish to know the incremental costs of providing an add-on real-time passenger information system or upgrading the OMC capabilities to provide full functionality.

The CIS costs of Phase VI can be used to estimate the incremental costs of full operations monitoring and control functionality, as shown in Table 5.6

Cost Type	Vehicle Costs	Control Center Costs
Hardware Costs ^a	\$604,000	\$102,000
Software Costs	\$133,000	\$299,000
Installation Costs	\$200,000	\$102,000
Operation Costs ^b	\$525,000	
Total Cost	\$2.0 million	
Cost/Vehicle	\$8,200	

Table 5.6: Incremental Cost Estimate of Full OMC^c

- a. 70% of hardware, software, and installation costs are assumed to go towards full OMC functionality
- b. 70% of operations costs are assumed to go towards full OMC functions
- c. It is assumed that field costs can be attributed to the general AVL system and thus are not included here

The Nag's Head expansion costs estimated by London Transport can be used to estimate the incremental costs of passenger information, as shown in Table 5.7

Cost Type	Field Costs	Control Center Costs
Hardware Costs ^a	\$1.2 million	\$81,000
Software Costs		
Operation Costs	\$1.2 million	
Total Cost	\$2.4 million	
Cost/Vehicle	\$6,900	

Table 5.7: Incremental Cost Estimate of PIS^b

- a. 90% of hardware, software cost, and 70% of operations costs are assumed to go towards PIS functions: bus shelter construction costs were NOT included in hardware costs

b. It is assumed that vehicle costs can be attributed to the general AVL system and thus are not included here

For both estimates, development costs were not included in the analysis. These estimates show that the incremental costs of full operations monitoring and control functionality are likely greater than the incremental costs for passenger information on a per vehicle basis, but not by very much. The difference in cost may be underestimated, however since the analysis reveals that incremental operations costs for PIS are higher than incremental operations costs for OMC. This may be because either London Transport may be conservative in estimating operations costs or the TTC may be underestimating operations costs. Also, the CIS costs were costs in 1986 while London Transport's estimates will be for the mid 1990's and in the ten year period between these estimates, hardware, software and labor costs may have changed dramatically.

Chapter 6

Summary and Conclusions

Rapid development in the information technology field has recently led many transit agencies to make decisions about implementing real-time systems and technology. Some make these decisions without fully assessing their needs, system requirements or the full effectiveness of these systems. This thesis has compiled and synthesized the bulk of literature related to this topic in order to aid agencies in choosing and implementing an appropriate real-time systems given the agency's operating circumstances. The thesis's findings are summarized below.

6.1 Potential for Information Technologies in Real-Time Operations

In order for agencies to maintain a high level of system performance, reliable service must be maintained on a day-to-day basis. This is no easy task since many situations in the field can and do occur that serve to cause unreliability in service. In response, agencies have developed many strategies to mitigate the effects of unreliability.

Many of these strategies need common types of information in order to be effective. One essential type of information is vehicle location information for determining schedule adherence and headways and for evaluating for strategies such as holding, short turning and expressing, as well as for providing dynamic passenger information. For some strategies to be effective, not only do these types of information need to be readily available, they need to be collected on a systemwide basis and conveyed quickly to decision-makers.

One principal use of this information is for monitoring operations and determining appropriate control actions. For these purposes, vehicle locations, headways and on-time

performance are crucial inputs with passenger loads, incidents on the network and vehicle status also being helpful.

A secondary use of real-time information is to provide passengers with forecasts of service quality. For this purpose, real-time information needs include estimated waiting times, passenger loads, and estimated travel times with estimated waiting times viewed as the most valuable type of information.

Advanced technologies have the capability of providing all of the needs of both operations monitoring and control and passenger information. With these technologies, information can be collected automatically on a systemwide basis. Advanced technologies can also relay information more quickly so that they can be acted upon more quickly. In addition, real-time passenger information can be provided in the form of estimates of vehicle arrival times, and this information can be relayed quickly to passengers.

6.2 Information Technologies

Agencies interested in implementing new technology have many choices in terms of types of real-time AVL systems, and not just in terms of vehicle location technology. Communications systems are needed to transfer location information to the right users, Computer hardware and software is needed to manage data that is collected, used and stored and choices on user roles and user interfaces have to be made as well.

There are many location technologies available on the market and the choice of technology must be based upon several factors including cost, accuracy and reliability. A comparative analysis of these technologies suggests that newer technologies such as GPS might well be less expensive and offer advantages over older technologies such as signposts and odometers, but risks are still involved because of the novelty of these newer

technologies. Hybrid systems are also recommended if high accuracy is required, but they will cost more.

There are also numerous communications technologies now on the market. A common problem in many communications systems is that of wave saturation, which constrains the number of wireless channels available to an agency. Many newer technologies improve on older technologies either by increasing channel capacities or improving transmission quality. Important issues in choosing communication technologies again include cost and reliability as well as availability. Comparative analysis between technologies suggests that conventional radios may not provide enough channel capacity which may force agencies to choose newer, more expensive technologies. Technologies that increase capacities may not be the sole answer to capacity problems and the reduction of data needs and transmissions is another method of solving capacity problems.

The computer hardware and software in an AVL system performs many critical tasks. Critical issues in choosing hardware and software are cost, location of equipment and system performance. Major tasks of hardware and software include collecting, processing and storing data, and providing user interfaces. Hardware and software are also responsible for tying systems together efficiently and effectively and providing full integration.

In a discussion that is filled with issues of a technological nature, it is easy to lose sight of the users who will have their roles changed as a result of these technologies. Inspectors may see a reduction or reorientation of their responsibilities, controllers may be able to make better decisions and operators may be provided a safer environment.

6.3 Case Studies

Three agencies which have had in-depth experiences with advanced real-time systems were investigated: the Toronto Transit Commission (TTC), the Ottawa-Carleton Transportation Commission (OC Transpo) and London Transport (LT).

TTC

The TTC employs an AVL system called CIS which has the primary function of operations monitoring and control. Vehicle location is determined by a signpost-odometer system that is received centrally on a 20-40 second polling cycle. Communications occur through 25 separate FM voice and data channels that use European technology to double capacity. A conventional cellular telephone is also installed on every vehicle as a backup voice communication system.

In the control room, controllers receive vehicle location and schedule adherence information as well as vehicle status and limited passenger load information. On the vehicle itself, schedule adherence data is presented to the operator who has various options for communicating with controllers. The entire system is managed through 15 IBM RT mini-computers networked together to provide redundancy.

Development, training and the installation of CIS occurred over a 15 year period and was quite successful. By breaking development into phases, and evaluating each phase before proceeding to the next, problems are resolved before they became critical. Some problems in development were due to time constraints, hurried training and recent cut-backs in staff.

Evaluations conducted after Phase VI was completed estimated the system-wide implementation of CIS to cost \$27.3 million, or about \$11,700 per vehicle. One of the primary reasons for the relatively high costs were the associated high development costs.

In terms of benefits, a TTC evaluation report estimated the quantitative benefits to have a monetary value of from \$6.6 to \$9.5 million annually, well above the estimated annual cost of CIS of about \$4.2 million. There were also other benefits of a non-monetary nature. A critique of the evaluation raised questions about the magnitude of some of these cost savings benefits and suggests a focus on service quality benefits rather than cost savings.

Opinions about CIS were generally positive. Managers and supervisory staff agreed that reliability has improved as a result of CIS but point to some remaining problems in the hardware and software. They note that CIS is just a tool for decision-makers, however, and thus the human element is the most important part of the system.

OC Transpo

OC Transpo decided to implement technology incrementally to aid in specific functions instead of creating a large integrated system like CIS. Each application of technology in OC Transpo's case solves a specific need of the agency. Recently, OC Transpo has been moving to integrate some of these systems in order to create a real-time AVL system with capabilities somewhat similar to the TTC's CIS system. The system under development at OC Transpo is called AVL/C.

One of OC Transpo's systems, a data collection system called APC, consists of a fleet of about 80 specially equipped buses, that utilize signpost-odometer technology combined with infra-red passenger counting devices. These devices work in tandem to collect detailed route information such as passenger loads and running times to generate reports of varying natures which are of great value in service and operations planning.

OC Transpo's 560 system is an automatic telephone information system that contains information about scheduled arrival times for every bus trip in the system down to the bus stop level. Telephones are placed at major bus stops, thus passengers can call a 560 num-

ber to hear information about scheduled arrivals. In this configuration, both pre-trip and at-stop information is possible with 560.

OC Transpo's AVL/C system builds upon systems currently in place that already provide some level of operations monitoring and control. The location technology of AVL/C is a passive identification system which uses infra-red readers combined with GPS boxes that transmit location information at a frequency proportional to the bus service frequency. The communications system will consist of an updated version of their current COBA system and will be made up of separate data and voice subsystems with voice communications operating on a priority scheme.

A centrally shared database links information from different modules and sources including a dispatcher/booking module, an Automatic Vehicle Monitoring (AVM) system identifying vehicles and comparing scheduled to actual times and a Service Control Module (SCM) which detects problem situations and informs controllers on an exception basis. The system is controlled by a network of VAX stations running under the VMS operating systems and using X-Windows as the graphical interface.

In an AVL/C environment, operator responsibilities will change very little, field inspectors will be used to validate AVL/C data and handle emergency situations and controllers will have better information for decision-making.

Overall, OC Transpo's systems have been effective at solving specialized problems and their strategy of applying technology specific to the task at hand seems to have been successful so far. They have had problems, however, in integrating systems, resulting in delays in system-wide implementation of the AVL/C system.

London Transport

The effects of privatization in London makes it more difficult to implement and integrate technology on a system-wide basis since competing operators might not be interested in sharing information or even in cooperating with each other.

Countdown is London Transport's latest initiative to provide a real-time passenger information system. Using signpost-odometer technology, a central processor takes location information and uses wait time algorithms to estimate bus waiting times which are then relayed to stops downstream displaying the estimated waiting times of the next three buses.

Overall, the personnel responsible for supervision and operations have favourable comments about Countdown. Controllers have had some difficulty in inputting and deleting messages but generally favor the system, as do most managers.

In evaluating the Countdown system, London Transport observed both the operational aspects of Countdown and its effects on passengers. Countdown met most of its targets on system reliability and availability but did not meet the ambitious predefined arrival time forecast accuracy targets. There were also no net ridership increases attributable to the passenger information system.

A stated preference "willingness to pay" analysis revealed that passengers valued the system at 26 pence per journey, although one must be wary about the results of such an analysis. Further passenger surveys revealed that 65% of respondents perceived shorter waiting times and 90% believed that the Countdown information made waiting more tolerable.

6.4 Framework for Agency Decision-Making

Before deciding upon a specific technology, the agency must determine the best role for technology to improve performance. If problems exist in the service planning function, non real-time data collection systems are generally likely to be more cost effective than either operations monitoring and control or passenger information. If the agency experiences service reliability problems, the best use for technology depends upon the causes of the unreliability. For systematic and predictable causes, non real-time systems may well be preferred. For real-time causes that can be controlled, using technology to perform operations monitoring and control is preferred, and if the causes are non-controllable, passenger information systems may be preferred. For other problems such as controlling operations costs, improving public perceptions and improving security, the preferred uses are operations monitoring and control, passenger information and operations monitoring and control respectively.

Some times, an agency will have several of these problems which may create the need to combine technological uses to solve them. If an agency has a problem in both public image and maintaining service reliability, then perhaps the most effective system would include both operations monitoring and control and passenger information capabilities. If an agency has a problem with the service plan and with service operations, the most effective combination may be an operations monitoring and control system with off-line data collection capabilities. In general, the more problems that can be effectively dealt with by a particular use of information technology, the stronger the case for that particular use.

After choosing the role for technology, the agency must define the general type of systems that is desired, which involves making choices on general AVL issues that will greatly affect functionality. There is first the issue of choosing between fully centralized

and partially decentralized systems. Partially decentralized systems have the advantages of less communications requirements and a better overall decision-making structure, but may suffer from possible increased hardware and software needs.

There is also the issue of substitutions between hardware, software and labor either to reduce costs or to increase performance. In general, hardware costs vary directly with fleet size while software does not and larger agencies have more reliability problems than smaller agencies. As a result, the larger the transit agency, the more cost effective it may be first to substitute hardware for labor, and second to substitute software for hardware.

Cost versus accuracy is another issue. An accuracy of about 60 meters is suggested as one that is both suitable for either OMC or PIS use and acceptable in terms of cost and feasibility. Both the older signpost-based systems and newer radio-navigation based systems can provide this accuracy cost-effectively.

The last issue involves the choice of discrete and quasi-continuous systems, and appropriate update frequency. Discrete systems are generally less expensive than quasi-continuous systems, but if update frequencies need to be increased, the added costs may be high. The required update frequency will generally depend upon the headway of the service, thus a system must be designed such that it provides either adequate updates for each route individually or a constant system update frequency that is appropriate for all levels of service.

One of the uses of AVL information is to aid in the operations monitoring and control function. Several purported real-time benefits of AVL information include improved schedule adherence, increased security, increased supervisory efficiency and improved work environments.

From the case studies, it is known that AVL systems probably improves schedule adherence but the extent of this improvement is still unknown. AVL systems also increase

safety and security. The TTC case study tells us there is not a lot of savings in manpower, but some efficiencies in terms of supervisor-to-manpower ratios are possible. Mixed views emerge about the changes to working environment with some supervisors missing the field contacts and becoming more stressed.

The benefits of passenger information are inherently different than the benefits for operations monitoring and control. For the most part, the effects of a passenger information system are not reflected in operations, but on the passengers themselves. Reported benefits of passenger information systems include positive influences on passengers in terms of decision-making ability, revenue from passengers willing to pay for information, improved passenger perceptions and attitudes and increased ridership. Market research reveals that although there is only limited travel time and wait time savings, passengers are willing to pay almost a quarter of their fare for passenger information and are generally in favor of real-time information. However, so far there have been no appreciable ridership gains, at least in London.

AVL system costs can be divided up into several categories: development, capital and on-going annual operating costs. Capital costs can be further sub-classified into vehicle related, control room related and field related costs. Development costs can be quite high if agencies wish to start from scratch, while agencies who wish to use already developed systems can incur large costs from consultants and experts. Costs can be estimated on a total or a per-vehicle basis and on a net present value or annualized basis. Costs can also be determined from a standpoint of functionality. By examining the costs of the TTC's CIS and London Transport's Nag's Head Scheme, it was concluded that in general, the incremental costs of providing full operations monitoring and control functionality is somewhat higher than the incremental costs of providing passenger information.

6.5 Areas for Future Study

While this thesis has covered a lot of ground in providing agencies with an initial look into the field of real-time technology applications to transit, there is still quite a bit of research left to be done. This thesis has identified many alternative location, communications, hardware and software technologies focussing on the most popular and currently feasible technologies. Further research could identify and evaluate future technologies that, although are not yet feasible, might become feasible and effective in the near future.

The same statement can be made for collecting certain types of information. Some information types such as number of passengers on board a vehicle are too expensive to collect presently, but could be feasible in the future. Further research could re-evaluate some of these information types should they become feasible.

In all three case studies, the agencies have not finished developing and refining their systems. The final word on the systems at Toronto, Ottawa and London has not been written yet with implementation and evaluations continuing. Further research should revisit these case studies and present updated evaluations and critiques. The same can be said for some of the other agencies listed, such as Denver and Dallas. This thesis has concentrated its analysis on signpost-odometer systems and further evaluation of the GPS systems of Denver and Dallas can shed more light on the cost effectiveness of this new technology.

As this thesis has shown, the potential of information technologies to the transit industry is great, but care needs to be taken in selecting the technology, and further research is needed to help achieve this full potential.

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