Using Design Structure Matrices to Improve Decentralized Urban Transportation Systems

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To my family
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Abstract

Management of large, complex, urban transportation systems involves numerous stakeholders due to the decentralized ownership and operation of distinct pieces of the physical network. In order to deliver better service to users, many urban regions are adopting technological and operational solutions, both of which necessitate interaction among the decentralized actors.

This research applies a systems engineering analysis technique—the design structure matrix (DSM)—in order to improve the efficiency and effectiveness of decentralized organizations involved in urban transportation as they deploy technology and attempt to integrate their operations. DSMs alone provide advantageous, straightforward system representation platforms. Furthermore, clustering algorithms can be applied to DSMs in order to identify potential opportunities to improve the institutional structure of the decentralized system of organizations.

We propose DSM representation and clustering as valuable methods for urban regions to identify organizational structures that facilitate both technology deployment through efficient utilization of resources and more effective operations through re-characterization of organizational linkages.

Thesis Supervisor: Joseph M. Sussman
Title: JR East Professor, Civil & Environmental Engineering and Engineering Systems
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During my first meeting with Professor Joseph Sussman as a graduate student, he posed the following question to me: what scale is most appropriate for management of transportation systems in urban regions? This thesis is the product of two years of thought and work stemming from that meeting. Along the way, Professor Sussman has provided invaluable intellectual guidance and financial support, for which I am most grateful.

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Chapter 1

Introduction

Many researchers have anticipated a shift in the nature of urban transportation from the provision of new, physical infrastructure to more effective operations of existing infrastructure. The scarcity of inexpensive, environmentally-durable, sparsely-populated land in much of the developed world—particularly in dense urban areas—provides economic, social, and political impetuses for placing greater emphasis on operations. Information and communication technologies represent fundamental enablers of the growing interest in improving the effectiveness of operations to increase network capacity.

Technology has long contributed to better operations of urban transportation services. Public-sector managers of transportation networks currently posses and/or soon will possess a wide array of options and opportunities for improved performance, from broadly-applied packages such as Advanced Traveler Information Systems (ATIS) and Advanced Transportation Management Systems (ATMS) to more narrowly-applied packages such as railroad-delay warning systems.

While the application of technology to physical infrastructure—dubbed Intelligent Transportation Systems, or ITS—has delivered and promises to deliver further benefits to
managers and users of the transportation system, it also promises to invite institutional difficulties. Functionally- and geographically-defined transportation providers have developed and refined their roles, responsibilities, and capabilities over many decades. Within a large urban region, for instance, dozens, even hundreds of organizations responsible for distinct pieces of the transportation network exist, from municipal transportation and public works departments to state departments of transportation to federal agencies. Urban transportation technologies often do not consider as constraints the informal, formal, and legal relationships among organizations that must deploy, manage, operate, accommodate, or perhaps even avoid the technology. One of the fundamental challenges for technology implementation, then, is not necessarily technical performance but institutional acceptance.

More recently, some researchers have suggested perceiving this challenge as an opportunity to integrate the functions of potentially-incompatible agencies through such mechanisms as Regional ITS Architectures. Although ITS creates some integration difficulties, it also provides the technical capability to build linkages and relationships that improve the effectiveness of transportation providers’ services. Regional ITS Architectures describe a region’s stakeholders and physical characteristics and specify connections among stakeholders that will, in principle, produce an integrated, seamless transportation system for users while remaining agreeable to existing organizations. Architectures include both a technical aspect and an institutional aspect; we focus our analysis in this thesis on the institutional aspect.

Although certainly helpful for structuring and managing the deployment of ITS in urban regions, architectures suffer several weaknesses. First, the prescription of connections is usually based on mutual, pair-wise agreement among stakeholders. In this thesis, we define stakeholders to mean only those organizations responsible for ownership, operation, maintenance, or other direct involvement with the transportation network. As a result, the architecture fails to capture potentially-critical relationships or collaborations that span the domains of more than two organizations (i.e., multi-lateral relationships). Secondly, the connections conform to the structure and alignments of existing organizations. While this approach increases the likelihood of agreement among stakeholders, it ensures that potentially more effective organizational structures—such as
the elimination of organizations, the creation of new organizations, or the revision of the mission or geographic coverage of existing organizations—will not be pursued as strategies. Third, architectures often leave deployment of technology and execution of the tasks they specify to the organizations themselves. Without external technical assistance, financial support, or motivation for action and change, this tactic often leaves agencies with little incentive to follow through on the recommendations or designs described in the architectures. Finally, as recognized and, to some degree, accommodated by ITS architectures, the existing structure of transportation organizations in urban regions is highly decentralized, yet many operations-management techniques require a centralized view of the transportation network. This mismatch invites consideration of strategies that provide a centralized perspective without compromising the autonomy or functionality of organizations in a decentralized institutional setting.

These weaknesses motivate the exploration of new methods for structuring regional transportation organizations in Regional ITS Architectures. We hypothesize the following:

- Design structure matrices (DSMs) are helpful analysis tools for representing complex, decentralized systems straightforwardly. Describing urban transportation organization relationships as DSMs is an improvement over existing description methods such as Regional ITS Architectures.
- Clustering algorithms for DSMs offer an opportunity to arrange a region’s organizations more efficiently than the ad-hoc methods currently pursued by ITS architectures that identify only pair-wise relationships; furthermore, clustering identifies potential multi-lateral relationships among organizations that are not recognized by regional architectures.
- Alternative, potentially more effective bases for integration strategies and identification of inter-organization connections than stakeholder-based analyses exist, including those based on physical connectivity and travel demand.
- DSM and DSM clustering satisfy more strongly and unambiguously the United States Federal Highway Administration (FHWA) requirement that ITS
architectures and deployment strategies follow a *systems engineering* approach.

To summarize, the above four hypotheses assert that DSM representation, DSM clustering, and consideration of network and travel-demand connectivity represent improvements to the current methods for prescribing organization-to-organization connections and institutional structures in urban transportation.

We measure the level of improvement that DSM clustering delivers to a region via three fundamental metrics: efficiency, effectiveness, and feasibility.

- *Efficiency* is a function of the cost of building a set of prescribed connections between and among institutions. *Connections* include physical linkages and institutional relationships. Measuring the cost of linkages, particularly relationships, which can range from informal cooperation as a response to incidents to formal agreements for shared control or maintenance, presents a challenge. DSM clustering, however, promises to produce a theoretically straightforward demonstration of more efficient and multi-lateral institutional structures.

- *Effectiveness* is a function of the ability of operating or controlling agencies to respond tactically to congestion, incidents, and other network conditions, and to develop strategic policies, standards, or operating protocols. Examples of tactics include traffic signal control coordination, dynamic route guidance, and distribution of information to users. Examples of strategies include integrated fare cards and electronic toll collection.

- *Feasibility* is a function of the acceptability of the proposed organizational arrangement by the organizations themselves.

We organize this thesis as follows. First, in Chapter 2, we present a literature review covering significant contributions to the understanding of the following topics: self-organizing and decentralized systems, appropriate scale of operations in complex systems (particularly urban environments), Regional Strategic Transportation Planning (RSTP), ITS architectures, and DSMs. Next, Chapter 3 provides a typology of decentralization that allows a clearer diagnosis of the type of environment in which urban transportation
organizations exist. Chapter 4 covers new methods for representing and analyzing urban organizations. It includes explanation of several types of DSMs and their possible application to urban transportation organizations, a summary of several clustering techniques, and description of techniques for measuring interconnectivity of sub-regions within an urban region as a proxy for the effectiveness created by their organizational linkage. Chapter 5 presents the results of the DSM clustering analyses and a discussion of their implications, while Chapter 6 evaluates the results and discusses their usefulness. Lastly, Chapter 7 provides conclusions and suggestions for further research.

Although DSM analysis constitutes a substantial portion of the analytical activities that support this thesis, it represents but one method for evaluating more tractably the problem of multi-organizational integration. The fundamental and original contributions of this thesis are the following:

- First, to characterize and explain decentralized interactions and their existence within urban transportation organizational environments;
- Secondly, to introduce DSMs and clustering analysis as potential tools for evaluating and improving the efficiency and effectiveness of urban transportation organizations by re-examining their relationships with one another; and
- Third, to suggest wholly-new, effectiveness-based criteria for determining the communication and data flow needs between organizations of an urban region attempting to plan for and deploy operations generally and ITS in particular.

Through these contributions, we hope to advance the pace of technology deployment and organizational integration in urban transportation.
Chapter 2

Literature Review

The *centralization versus decentralization* debate recurs in government, business, and many transportation modes. Decentralization emerges in complex systems when the system grows too large or complex for a single, centralized controller to manage multiple, independent actors effectively. Decentralization may also emerge naturally in a small system that grows and self-organizes. Conversely, poor performance in the presence of too many decentralized, interconnected but uncoordinated actors often necessitates more centralized control.

Literature covers decentralization as a phenomenon and a strategy within a variety of contexts. This chapter summarizes literature from several fields, but focuses ultimately on decentralization in urban transportation and methods for dealing with the challenges that decentralization creates. After beginning with a description of self-organization and emergent behavior in Section 2.1, the discussion then presents historical efforts to determine optimal sizes for cities and nations in Section 2.2. Given the inconclusiveness of such efforts, Section 2.3 discusses decentralization as a management strategy for overburdened transportation systems. To bring the discussion of decentralization closer to urban transportation, a description of Regional Strategic Transportation Planning (RSTP) as a special case of Complex, Large-Scale, Integrated, Open Systems (CLIOS) is included in Section 2.4. Next, Section 2.5 summarizes Regional ITS Architectures.
Finally, Section 2.6 describes the use of the design structure matrix (DSM) as an analysis tool for decentralized and modularized industrial and product-design processes.

### 2.1 Self-organization

The self-organization principle maintains that many complex phenomena exhibiting characteristics of a centrally-controlled system can, in fact, operate without a true “leader.” Rather, each component operates according to its own set of procedures, rules, or instincts. Together, the components display a seemingly-high level of coordination that suggests the existence of a centralized authority. Common examples include biological phenomena such as flocks of birds, ant colonies, and an organism’s immune system; natural phenomena such as hurricanes; and sociological phenomena such as highway traffic.

MIT researcher Mitchel Resnick conducted a series of self-organization studies and developed a software program, Starlogo, which enables users to observe the emergence of self-organizing behavior in simulated decentralized systems. Among other observations, Resnick points out that the human mind tends to ascribe a centralized structure to complex and poorly-understood situations. By extension, many observers deduce that it is reasonable to apply a centralized structure to complex and poorly-understood situations. In reality, however, many coordinated systems lack centralized control and, likewise, some complex systems may not necessarily benefit from centralized control schemes. Resnick’s software encourages users to liberate themselves from a centralized mindset by modeling self-organizing systems such as ant trails, pond ecosystems, and traffic jams. By assigning a set of individual operating rules to each actor in the system, users can then observe the emergence of coordinated behavior seemingly but not actually dictated by a central authority.

Several researchers suggest the existence of self-organization in transportation. Zhang and Levinson, for example, use an iterative transportation and land-use model of a metropolitan area and its road network to observe the emergence of road hierarchies. Their simulated approaches suggest a correlation between the observed evolution of roadways and the model-based predictions of network expansion. The model-based predictions were self-organizing in the sense that observations of investment in and
expansion of high-demand pieces of the network emerge from within the system rather
than according to a centralized algorithm. From the perspective of transportation
institutions, Donald Chisholm performed a study of Bay Area transportation agencies in
the 1980s. At that time, state and some metropolitan political bodies were considering
the creation of a new, high-level coordinating body to govern the complex interactions
among a set of agencies and operators in a hierarchical, top-down fashion. His analysis
suggests a non-hierarchical structure that, instead, facilitates lateral coordination of
institutions and agencies. In effect, theirs would be a self-organizing coordination that
emerges absent direction from a central authority.

Since some phenomena exhibit self-organizing characteristics, including conceivably
the formation of cities, it is reasonable to ask whether such systems ever exceed a size
such that purely decentralized control becomes ineffective or unsustainable. In other
words, can self-organized systems outgrow themselves? Is there an optimal size for cities
or urban transportation networks generally? Is there an optimal size for managing them?

2.2 System size and structure

Given the existence of an optimal size for a city or network, leaders could likewise make
their management closer to optimal by designating appropriately-sized jurisdictions as
controllers of particular pieces of the network. Researchers have considered the question
of optimal size in a variety of fields, but thoughts on the topic extend as far back as
classical times. Although short of providing a definitive answer, these thinkers
considered interesting questions and provide criteria, methods, some results, and
discussion of trade-offs related to optimal system size and structure.

Plato’s efforts represent perhaps the earliest calculation of optimal city size. In Laws,
the eminent Greek philosopher proposes 5,040 heads of household as the ideal population
of a settlement. His selection of this number is more “convenient” than optimal,
however, and the logic to arrive at it omits some significant considerations. Four
fundamental criteria underlie the formulation: first, that there be enough territory to
accommodate citizens “in a moderate way of life”; secondly, that the population be large
enough to protect itself from the encroachment of its neighbors; third, that the population
be large enough to deliver aid to beleaguered neighbors; and, finally, that the number be
easily divisible by a large number of divisors. Another important consideration of city size relates to the form of government of its people, the best of which according to Plato follows the aphorism that “Friends have all things in common.” Although compelling, these criteria fail to explain the ultimate, somewhat arbitrary selection of 5,040. There are, after all, other numbers that meet the criteria.

After extolling the virtues of the convenience of the number 5,040 and the ease with which it allows the administration of various municipal functions, Plato briefly describes his physical vision of the city. The center of the city, itself located as near to the center of the “country” as possible, consists of a collection of civic and religious monuments called the Acropolis. Twelve sections, divided by radial lines, emanate from this point.

Individual plats, or lots, are designated as follows:

...Each of [the 5,040 lots] shall be divided into two, and every allotment shall be composed of two such sections; one of land near the city, the other of land which is at a distance. This arrangement shall be carried out in the following manner: The section which is near the city shall be added to that which is on borders, and form one lot, and the portion which is next nearest shall be added to the portion which is next farthest; and so of the rest... And [the legislator] shall distribute the twelve divisions of the city in the same way in which they divided the country; and every man shall have two habitations, one in the centre of the country, and the other at the extremity.

Confident of his logic, Plato even suggests methods for maintaining careful equilibrium of the 5,040 households, including strict adherence to primogeniture with respect to the lots, reproductive restraint during times of overpopulation, and “sending out a colony” as an extreme measure for dealing with growth.

Ultimately, Plato offers little guidance for the physical infrastructure of his ideal settlement, instead focusing largely on less tangible community needs. For instance, he fails to address the problem of transportation of residents between their allotted spaces and other sites such as neighbors’ homes, markets, and the Acropolis. Nevertheless, his relatively unsophisticated attempt to describe a city with ideal characteristics significantly predates economists and geographers, who offer more recent explanations and descriptions of settlement sizes in a far more technical and quantitative manner but less conclusively with respect to the optimal.

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5,040 is evenly divisible by 59 divisors, including 11 of the first twelve counting numbers.
During the last two centuries, economists have attempted to describe the location, size, and growth of cities. In the tradition of J.H. von Thünen, early central place theorists represented the world as a flat, homogeneous plane with equal distribution of resources. Three factors of production—land, labor, and capital—underlie neoclassical thinking and govern location decisions in central place theory. Producers seek to maximize profits by locating so as to minimize their production costs and expand their market areas. Firms compete for cheap factors of production within and among regions in order to expand their scope and earn increasing returns as they expand.

Building on early theories, August Lösch, a German economist, derived a structure for the location of firms based on profit maximization, production costs, and transportation costs. In this structure, firms “repel” one another in order to capture markets, resulting in a distribution of firms (and also of markets and cities) throughout the plane. As one contemporary economist observed, however, “Within metropolitan areas themselves it is not easy to discern the hierarchical pattern of market areas (and of centers) for the distribution of goods and services.” In other words, the density of population and ease of travel preclude understanding intraregional or intraurban phenomena under the central place theory framework.

Central place theory was also advanced by Walter Christaller, who developed a model of hierarchical market centers. Multiple centers exist across the von Thünen plane, each one performing a specific function (producing a good or service) according to its prominence in the hierarchy. The form of this arrangement manifests itself geographically as a honeycomb, and more accurately describes actual urban conditions than Lösch’s model. In addition, since factors of production are mobile, labor and capital will migrate to new firms within regions and to new regions altogether for higher wages and better returns.

All this suggests that a limit exists to the optimal size of a firm, city, or region. Although the optimum itself is not suggested in any of the literature, central place theorists at least provide a framework for considering the underlying economic forces that drive the factors of production toward or away from population centers.

More contemporary regional theorists view economies outside of the constructs of central place theory and offer a more coherent explanation of some intraregional
phenomena. Several theorists suggest that similar firms are attracted to the same region, rather than being repelled by one another. Michael Porter, for instance, articulates the phenomenon of “clustering,” whereby many firms locate near one another in order to take advantage of common benefits. They are linked by “commonalities and complementarities.” Benefits of clustering include a network of knowledge in the local community, cultivation of a workforce well-trained in a particular field, and availability of other resources necessary for efficient production such as transportation infrastructure. Clustering includes localization economies, in which similar firms co-locate, and urbanization economies, in which firms producing different products locate near one another. In either case, clustering suggests that cities can incorporate both similar and dissimilar firms and expand broadly.

On the other hand, there are economic advantages to the dispersal of production activities. Karen Polenske, for instance, describes dispersal economies, where firms and groups of firms gain cost savings by dispersing specific functions spatially, and connecting the functions with a supply chain. This configuration presents an opportunity for regions to compete for different types of firms through provision of infrastructure that supports efficient supply chains, thereby suggesting that economic expansion can occur absent heavy growth and centralization in a single city.

Economists widely hold the view that “increasing returns to both individual plants (economies of scale) and spatial ensembles of economic activity (agglomeration economies) are positively associated with size and hold over a fairly sustained period of development.” Pulling in the opposite direction are diseconomies of scale, such as “congestion, high factor costs, and the absence of amenities which may encourage firms to... move elsewhere.” Ann Markusen conducted case studies of Brazil, Korea, Japan, and the United States to illustrate the relative successes and failures of national policies that encourage growth of “second-tier” cities. Without national intervention, the pull and push of economies and diseconomies suggest that equilibrium can be reached whereby some investment in the dominant city of a country relocates due to the drawbacks of “hyperurbanization.” At the same time, however, empirical evidence suggests that, particularly for developing economies, the centripetal forces of the dominant central cities preclude significant decentralization of investment, population,
and economic growth to other cities outside of the center. In economic terms, the
tradeoff between agglomeration’s benefits (e.g., knowledge networks and close proximity
of suppliers) and costs (e.g., congestion and pollution) can be represented as in Figure
2-1. The “optimal” size for a city lies at the intersection of the marginal cost and
marginal benefit curves; unfortunately, economists concede that locating this point is a
practical impossibility.11

![Diagram of marginal costs and benefits of agglomeration]

**Figure 2-1: Economic perspective of the size tradeoffs for a city**

Arriving at a similar category of conclusions from the perspective of cognitive
psychology, Malcolm Gladwell explores optimal colony size in a section of *The Tipping
Point*.12 He describes channel capacity, a phenomenon that researchers observe as the
limit on the capability of the human mind to handle complexity. Evolutionary biologists
observe that early humans lived in small communities and traveled over small distances,
for instance, characteristics that stay with us. Interestingly, some scientists further
hypothesize that a “social channel capacity” of roughly 150 exists for humans, a number
derived from the size of the neo-cortex of the brain. The number is confirmed
empirically in several societies that limit the size of their colonies to 150. Even a modern
American corporation, Gore-Tex, limits the size of its factories to 150 employees.
The framers of the United States Constitution debated optimal governance as they negotiated the extent of powers accorded to the national government. Anti-federalists argued that, together, the territory of the thirteen colonies comprised too expansive and heterogeneous a space to allow a single government, particularly a democracy requiring the participation of all citizens. For instance, the Centinel #1 states, “a very extensive country cannot be governed on democratical principles, on any other plan, than a confederation of a number of small republics, possessing all the powers of internal government, but united in the management of their foreign and general concerns.” By extension, the author argues that unification of any territory so expansive would certainly result in despotism. In The Federalist Number 14, James Madison counters that the proposed republican government does not require the participation of all citizens and that, furthermore, the nation compares favorably in size to others with national governing bodies such as Germany and Poland. He contends that the functions of the national government will be limited so as to preserve the individuality of the component colonies. Furthermore, “the intercourse throughout the Union will be facilitated by new improvements” such as interstate roads, canals, and faster communication across the territory.

Two centuries later, in the 1970s, Robert Dahl and Edward Tufte undertook a study of country size and its relationship to political, economic, and social characteristics. They began by asking what range of population is appropriate or optimal in order for democracy to flourish. Small democracies should inspire more citizen participation, but lack the resources necessary to address large-scale problems or to implement large-scale projects and programs. Given the large size of the United States compared to smaller European democracies, the study considers the relative strengths and weaknesses of each that stem from their respective sizes.

Dahl and Tufte offer some interesting conclusions. First, they found that local governments enjoy greater success in encouraging citizen participation, but that citizen participation in national government activities does not vary significantly with size. Secondly, they decline to suggest an optimal size for a nation that bolsters its ability to sustain democracy. Democratic regimes adjust to their needs by negotiating with citizens, altering boundaries of political units, creating new political units within large
ones, creating new political units that unite smaller ones, and perhaps even separating systems into multiple, interdependent systems. In government theory, the prevailing view for over 2000 years asserted the city-state as the ideal political unit. In roughly the last 200 years, the nation-state replaced the city-state on that pedestal. Yet, throughout history, small nations have joined compacts and become absorbed into larger nations out of convenience. The opposite has also been true as sub-units have often successfully achieved political independence from a larger unit of government. Given the "competitive region" described by Porter, perhaps the earlier model of the city-state is re-emerging in an era of globalization and greater international competition for labor and capital.

Alesina and Spolaore undertake a similar effort to Dahl's and Tufte's in their text *The Size of Nations*. Like their predecessors, Alesina and Spolaore "raise more questions... than we have answers," noting the dearth of research on the question of nation size. Nonetheless, they offer several observations. For example, the size of a nation depends on the tradeoffs between "the benefits of economies of scale... versus the cost of heterogeneity of preferences in the population." Interestingly, they note that one feature of nation-states that lends itself to economies of scale is national defense; that is, the costly nature of military suggests that large countries have less difficulty raising and maintaining armies. Likewise, reductions in the threat of conflict reduce the size of nations, as evidenced by the separation and creation of dozens of new nations in the wake of the Cold War: "A more peaceful world can be organized in smaller and more numerous states." Smaller size allows nations to deal with taste heterogeneities since economies of scale are less necessary when armies are not needed. The authors identify federalism and internal decentralization as techniques for dealing with the dual problem of economies of scale and population heterogeneity, but caution that centralized delegators often fail to provide the resources necessary for the operation of decentralized layers.

Whether considering towns, cities, regions, or nations, the work of philosophers, economists, and political scientists fails to answer definitively the question of optimal size. The work does, however, provide a characterization of the numerous tradeoffs between size and manageability; location and prosperity; and geography and institutional
effectiveness. Given the large size or extreme complexity of a system, subdivision into less complex systems represents a reasonable approach that requires techniques for managing multiple, decentralized, and inter-connected subsystems. The next section discusses decentralization as a management strategy through several real-world examples.

2.3 Transportation decentralization experiences

Given significant complexity, there are several ways to conceptualize subdivision of a system into more tractable subsystems. For example, partitions can occur geographically, as in the case of expansive systems such as national governments or roadway networks. Functional decentralization becomes useful in the case of, for instance, designing a complex, multi-function product. Hierarchical decentralization provides a layered approach to a system by separating higher-order from lower-order tasks and functions. This typology can be applied in order to simplify analysis and/or management of any number of complex systems. This section summarizes several cases of decentralized analysis and management, from business to transportation generally to ITS in particular.

2.3.1 Centralization vs. decentralization in railroads

Following a trend of increasingly centralized management in the railroad industry, the Union Pacific Railroad (UP) opened a command center at its headquarters in Omaha, Nebraska in 1989. From the command center, UP managed all dispatching on the rail network but also crew scheduling, maintenance scheduling, and other operating functions.\(^{14}\)

In the fall of 1997, several months after beginning a historic merger with the Southern Pacific Railroad, UP experienced an unprecedented service crisis. Congestion on its rail network that began between Houston and New Orleans spread over several weeks across the entire network. The congestion problem, compounded by a series of accidents, continued for a year as managers attempted to locate lost cars, unravel congested corridors, and establish a more reliable operating strategy. Observers of and participants in the UP service meltdown attributed many of the operating difficulties to the shock of managing an extensive new post-merger network.\(^ {15}\)
As part of its response to the service crisis, UP began major restructuring of its operations that shifted management from a centralized configuration to a more decentralized one, putting greater emphasis on the power of local managers to make decisions. By 2001, UP had designated four operating regions, each with its own headquarters. Pinpointing an overly-centralized management structure as the only cause of service problems would be overly simplistic. Nevertheless, UP’s response—to divide its network into regionally-managed components—suggests that centralized managers were overburdened and ineffective enough to make decentralization appropriate.

While dispatchers still work at the command center in Omaha, each reports to regional executives for one of four regions. The company still produces standards in a centralized manner to ensure cohesiveness among regions, but day-to-day operations no longer follow a command-and-control decision-making model. Instead, regional managers exercise greater control over their portions of the network.

2.3.2 Centralization vs. decentralization in air traffic control

As with UP, air traffic management derives benefits from a decentralized structure, which “enables local flexibility and a tailoring of services to meet the needs of users at the local level.” American airspace is managed by the Federal Aviation Administration, but communications and daily operations are delegated to subregions, most notably the 20 Air Route Traffic Control Centers (ARTCC’s, or Centers) throughout the lower 48 states. Meanwhile, a centralized feature, the ATC System Command Center located in Herndon, Virginia, monitors air traffic conditions and incidents system-wide, although with much less detail. There are several layers of air traffic control in addition to the Centers, including control towers, terminal radar approach control centers, and flight service stations. Each facility offers a specific service or covers only a specific piece of airspace.

An aircraft traveling between Centers typically ends communication with one Center and initiates communication with another as it passes between them. Center computers, which contain flight paths, weather information, and other data, “do not overlap in coverage or information with other Centers.” The operational relationships between
bordering Centers are governed by predefined standards and practices, developed and agreed upon by the Centers themselves. Such compartmentalization allows for strong local control of traffic, overseen but not directly controlled by a single, national command center.

The airline industry itself manifests aspects of both centralized and decentralized operations. Consider, for instance, the gate operations of Southwest Airlines, a low-cost carrier whose route network follows a point-to-point model. Managers have granted decision-making power for gate operations to agents at each gate. American Airlines, on the other hand operates a traditional, hub-and-spoke route network. Control of such functions as holding aircraft for connecting passengers is exercised by managers at a central location, with the help of optimization algorithms. The distinct approaches—one decentralized, the other centralized—are functions of the types of network operated by the two airlines, and demonstrate the importance of context in determining a management approach.

**2.3.3 Centralization vs. decentralization in ITS: ATMS**

In urban transportation, various ITS applications and technologies exhibit decentralized and potentially-decentralized features. Two packages of technologies—ATIS and ATMS—comprise the bulk of anticipated ITS applications for urban transportation. ATIS includes collection, distillation, and dissemination of information to drivers on the roadway network. ATMS, on the other hand, uses information and forecasts of travel conditions in order to implement management strategies such as traffic diversion, traffic light settings, and general route guidance in real time.

ATMS aims to reduce congestion by providing real-time guidance and information to drivers on urban road networks such that demand is distributed optimally across the network. Advantages of these services include diverting traffic around accidents or work crews and suggesting alternate routes for drivers approaching congested areas. More generally, ATMS makes more efficient use of existing roadway capacity in urban areas whose highways and arterials often suffer congestion even as parallel routes have unused extra capacity.
The components of ATMS include data collection equipment and infrastructure; algorithms that estimate future traffic conditions and optimally allocate travel demand to the roadway; and communications linkages that transfer data between vehicles on the network and computing facilities. ATMS might proceed as follows on a typical day:

- Access historical traffic flow and current traffic flow data;
- Estimate future traffic conditions based on these data;
- Suggest management strategies such as re-routing of vehicles on the network, changing of traffic-light and ramp-meter settings, and incident response; and
- Communicate these suggested strategies to the infrastructure and to drivers via variable message signs (VMS), in-vehicle devices, or other forms of communication.

Each step in the process requires time, particularly the computationally-intensive steps of predicting future traffic and suggesting guidance strategies, creating a fundamental trade-off between the ability to compute strategies quickly and to provide effective strategies.

Underlying the computational steps of ATMS are simulation software programs such as DynaMIT, DYNASMART, Paramics, TRANSIMS, and AIMSUN. Each of these programs differs in the way in which it simulates traffic, but all share a fundamental commonality: a potential application in real-time management scenarios such as ATMS. Consequently, simulation speeds must at least match real time. In fact, given the other time-consuming steps in the ATMS process and the dynamics nature of traffic information, urban regions require traffic simulators that outpace real time.

To that end, researchers have formulated and considered a variety of strategies for increasing the speed of computation without trading off the quality or integrity of simulation results. Other than applying brute computational force, which can be costly, a common approach conceptually is to distribute the computational burden across a smaller portion of the roadway network and assign a processor to each sub-network.

Motivated in part by the issue of computation time, Hawas and Mahmassani (1995) developed a distributed-control architecture for a route guidance system. They characterize their concept as a contrast to the “commonly encountered (centralized control) approach” for ATIS and ATMS. A distributed approach offers “substantial
reduction of dimensionality in control problems” and allows for “individual local solutions [which] could be combined into a solution for the overall system.”

The distributed architecture of the route guidance system involves several local controllers rather than a single central controller. Each local controller uses only partial information on current network conditions and origin-destination trip demand. Figure 1 recreates the scheme as envisioned by the authors, where the local controller represented by a node only has network-state and OD-trip information for the area within its local area represented by the dark-shaded oval. The architecture is non-cooperative in that “controllers work in a pure independent environment, and [are] assumed to hold no complete or perfect knowledge regarding the network conditions…”

After developing three distinct “local rules” for operating the guidance system, the authors tested each scenario using a hypothetical network of a freeway and parallel routes divided into ten sub-networks, each containing between one and four nodes. The first local rule assigns traffic from the decision node to the link with the shortest travel time; the second assigns a portion of the traffic leaving a decision node outbound links according to a logit-type model; the third assigns traffic according to travel time and “concentration,” a rough measure of potential future congestion. Average travel-times measured in the experiment varied for different local rule and other parameters, although no experiment with decentralized control outperformed the case of centralized control.
Pavlis and Papageorgiou (1999) similarly recognize the inability of overburdened computational systems to provide useful guidance. They propose a feedback strategy similar to that proposed by Hawas and Mahmassani in that decision-making occurs at nodes in a network rather than at a central controller. Hawas and Mahmassani, however, do not consider the consequences of congestion outside of a local area for decision-making within it:

...this kind of geographic decentralization runs the risk of ignoring or underestimating the delays caused by (possibly nonrecurrent) congestions that may be present outside the considered limited area, in which case the strategies may deliver inappropriate guidance instructions.

Pavlis and Papageorgiou report on the effectiveness of “simple decentralized control laws... for route guidance in complex, densely meshed networks.” They found that such laws “appear sufficient” for achieving dynamic user-optimal conditions. Furthermore, the node-based control laws allow for “extension of the traffic network... [without requiring] a complete redesign of the overall strategy.” In other words, the decentralized configuration adds another benefit beyond time savings: greater flexibility to expand.

Like the previous two sets of authors, Minciardi (2001) proposed a decentralized scheme for reactive route guidance based on splitting rates at decision nodes in the...
network. Minciardi's algorithm and proposed optimization formulation differ from those proposed by other researchers, but the ultimate result—user-optimal travel times between decision nodes and destination nodes—is similar. The difference is that the algorithm allows for communication of local travel times between neighboring nodes, a concept that becomes important in hybrid models, discussed later in this section.

Some researchers focus explicitly on the question of electronic processing capacity by considering new computational architectures for route guidance software programs. Lee and Chandrasekar (2002) describe existing opportunities for parallel computation in three microscopic simulation traffic simulation packages—TRANSIMS, AIMSUN, and Paramics—and propose a broader framework for implementing parallel computing in a generic software program. The authors tested their proposed configuration under several distribution scenarios (one, two, and three processors) and concluded that the computational performance improved in the parallel cases at least as much as 50%. With three processors, speed improved from 175 to 375% over the case without parallel processing.

Citing a particularly pessimistic view of the ability of processors to keep pace with computational load requirements for transportation simulation, Liu, et al. (2005) propose a framework for parallel processing similar to Lee and Chandrasekar. They provide a conceptual illustration of the motivation for decomposing route guidance problems (re-created in Figure 2-3). On the far left, they represent a simulation problem as describing state variables over time (“filling up the variable space”), with the state variables represented on the vertical axis and simulation time on the horizontal axis. In the middle, the problem can be decomposed temporally; on the far right, the problem can be decomposed spatially. When decomposed temporally, the state of the entire network must agree at points in time between each decomposed piece of the problem. This is roughly the formulation developed by Peeta and Mahmassani (1995), who labeled their dynamic traffic assignment (DTA) software implementation a “rolling horizon” approach. On the other hand, under spatial decomposition, boundary conditions must satisfy the state of the network at its physical sub-boundaries as time progresses simultaneously for each physical sub-component.
Recent attempts to decentralize networks and DTA computations often combine central and local layers into a hybrid system. Chiu and Mahmassani (2001) provide a modeling framework of such a system along with performance test, while Farver (2005) takes a different approach at specifying the behavior of the decentralized control layer.

Chiu and Mahmassani (2001) describe a framework for hybrid DTA implemented in DYNASMART. The framework envisions two layers of traffic guidance. First, a centralized layer provides predictive information such as traffic conditions and the demand for and supply of network capacity. This layer requires heavy inputs of information and is subject to low reliability (e.g., if the central control layer breaks down, no drivers receive guidance). Secondly, a series of local, decentralized layers provides reactive guidance (e.g., without demand predictions). Instead, "distributed routing agents usually seek local optimality based on their individual objectives," a process that the authors admit leads to the "non-cooperative nature of operations" and that is "inherently suboptimal" across the broader region. On the other hand, the local layers require less burdensome information inputs and computations and provide a more fault-tolerant system than the central layer: "If one or several controllers fail, the entire network can still be operational with some adjustments.” The algorithm for hybrid control developed by Chiu and Mahmassani is based on game theory: the center layer, or leader, solves an objective function to minimize travel time for vehicles assigned to the central layer in system-optimal manner; each decentralized layer, or follower, solves separate objective functions. Vehicles on the network receive guidance from only one of the two layers.
By varying the initial routing profile (IRP), or percentage of vehicle receiving central guidance, the experiments measured average travel times on a simulated network in DYNASMART for two types of vehicles: those receiving central guidance and those receiving local guidance. Presumably vehicles traveling outside of any given local area received central guidance, while those vehicles with both origin and destination located entirely within one local area received guidance from a local controller. These assumptions are in line with the authors’ finding in the literature that “decentralized routing is suitable for local traffic control but may not be satisfactory as the sole traffic routing framework for the entire network.” The leader and followers then “compete to (sic) each other in utilizing network capacities.” Although the authors maintain that leader and followers are not “strictly against” one another in this framework, competition between them exists, and test results indicate that vehicles receiving guidance from the leader experience lower average travel times than those receiving guidance from followers. However, when the authors introduced prediction errors into the predictive component of the central layer, they found that performance overall was best when only 50-60% of drivers received central guidance and the rest relied on local, reactive guidance.

More recently, Farver (2005) developed a hybrid centralized-decentralized framework for route guidance using DynaMIT as a platform for experimentation. Farver’s work prescribes a decentralized layer at the level of the vehicle, which provides reactive guidance in local area, and a centralized layer that provides predictive guidance system-wide. In Farver’s formulation, one of the primary advantages of the centralized layer is to ensure consistency, the notion that guidance and predicted network states are based on a process that considers drivers’ reactions to route assignment strategies iteratively during computation. Because of the long time required to compute such strategies, however, their usefulness cannot be guaranteed to drivers, as traffic conditions change quickly and incidents may occur in the interim. To augment the centralized guidance, then, the vehicle-centric computation layer measures conditions by communicating with other vehicles within a prescribed spatial radius. Reactive guidance based on this local information is computed within the vehicle. Such an arrangement differs from Chiu and Mahmassani in several ways. Most notably, drivers in Farver’s
hybrid framework receive guidance from both central and local control layers. Secondly, consistency is ensured at the central layer. Finally, computation at the local layer does not occur across a geographic subset of the network, but rather by and within the vehicles themselves. Both hybrid approaches do, however, share some common advantages, such as redundancy and greater system reliability.

For over a decade, researchers have recognized the issue of computation speed as a barrier to the ultimate implementation of route guidance. According to Moore’s law of increasing computer power, processing speeds should have increasing more than 100-fold in that ten-year period. Yet, even today, most researchers still acknowledge that strategies other than real-time, centralized, single-processor computation of route guidance for our highly-complex traffic networks are required. To that end, concomitant with the development of software packages and their prediction and estimation capabilities, much work has identified strategies for feasible, real-time execution of guidance and control algorithms computationally. Although many of the distributed or decentralized formulations under-perform fully-centralized formulations, they do offer a useful technique for time savings. Even more promising, however, is the combination of central and distributed computational layers into hybrid route guidance systems, which enjoy the computability and scalability of local control yet retain many of the benefits of optimal, centrally-performed route guidance.

2.3.4 Section Summary

As seen in most of these cases, complexities resulting in inefficiencies and sluggish response times drive the decentralization of systems. Conversely, maintenance of some form of centralized authority or structure is universal, from railroads with their standards and procedures to ITS route guidance with its reliance on a central perspective for consistent and better-coordinated management.

2.4 Regional Strategic Transportation Planning (RSTP)

Federal law in the United States requires metropolitan areas to complete and regularly update a long-range transportation plan. Most areas designate a Metropolitan Planning Organization (MPO) to carry out the planning process. Complexities of long-term
planning include the technical challenges of population growth and travel-demand forecasts, financial constraints, and competing stakeholder interests. Traditionally, advances in long-term planning stemmed from the development of techniques for locating and prioritizing infrastructure growth and expansion. In response to some of the difficulties and deficiencies of current practices, some researchers have suggested alternate frameworks for the creation and realization of transportation plans, such as the RSTP framework proposed by Sussman.

Sussman, Sgouridis, and Ward consider RSTP as a special case of CLIOS.\textsuperscript{28} CLIOS analysis involves a twelve-step process whose pieces can be simplified into three fundamental steps (representation, evaluation, and implementation) summarized in greater detail in Figure 2-4.
As a special case of CLIOS, RSTP requires analysis according to a similar framework. As such, Sussman, Sgouridis, and Ward developed a conceptual representation of the RSTP process and its outputs, which includes an operations plan. The operations plan, as opposed to an infrastructure plan, lays out the operational requirements of the transportation system. Eventually, the operations plan can be translated into a regional operating architecture and, ultimately, implemented as part of
the day-to-day operations of the transportation network. Currently, many long-range plans neglect the operational aspect of urban transportation and focus their efforts instead on infrastructure planning. Operations, after all, occur within a much faster timeframe than infrastructure planning and construction. Nonetheless, the paper provides a framework within which to consider the importance of planning for operations. Figure 2-5 provides an overview of the RSTP process, including the output of an operations plan.

Figure 2-5: RSTP process

Source: Sussman, Sgouridis, and Ward.

2.5 Regional ITS Architecture

Another output of planning at the regional scale is the Regional ITS Architecture. As stipulated in TEA-21, FHWA and FTA issued rulings requiring regions to develop a Regional ITS Architecture by April, 2005. The regulations require these architectures to conform to nationally-defined standards and meet other specific content criteria in

\[\text{\textsuperscript{[29]} For regions yet to undertake any ITS projects, the deadline is four years from the date the project advances to final design.}\]
order to maintain eligibility for federal ITS funding. Although architectures include both technical and institutional aspects, we are interested primarily in the institutional implications of ITS architectures.

The architecture development process follows a series of steps and produces deliverables at each stage, beginning with a needs analysis. The needs analysis identifies all anticipated ITS projects in a region and the needs associated with those projects. Next, based on the needs analysis, the region develops a Regional ITS Architecture which "defines existing and planned component systems and the interfaces among them." Lastly, based on the ITS architecture, the region will develop both an operational concept and an implementation plan. Figure 2-6 summarizes this process.

While the implementation plan describes a strategy for realizing the systems specified in the architecture, the operational concept describes roles and responsibilities of specific stakeholders in the region. For example, stakeholders discuss how they will each respond under scenarios such as a "large weather incident, hazardous material spill, or long-term construction project."30

Figure 2-6: Architecture Development Process

Throughout the ITS architecture development process, FHWA provides standards, technical assistance, examples of best practices, and other resources, but ultimately the responsibility to develop architectures rests with the regions themselves, usually a state transportation agency or MPO. In turn, these public agencies often contract drafting of architecture documents and technical specifications to vendors with domain expertise. According to the most recent deployment data, 164 out of 311 states and metropolitan areas have Regional ITS Architectures considered “ready for use.” Another 110 are under development, and 18 have not yet started. This suggests that, although many regions have yet to complete their architecture documents, most have moved into the stages of developing implementation plans and operational concepts.

Architectures themselves are descriptions of the required information flows and communications linkages between the numerous decentralized agencies, jurisdictions, and other managers with responsibility for some piece of the transportation network in a region. For example, entities cross-communicating might include a municipal fire department, a county maintenance agency, a state department of transportation district, an MPO, a tolling authority, a sheriff’s office, a transit operator, local media, and vehicles on the network. Even this short list of potential participants highlights the breadth and complexity required of the communications protocols and procedures, particularly for large metropolitan areas with many overlapping jurisdictions. Still further complexity results when one considers the array of functions and technologies included in an ITS package, such as ATIS and ATMS (which may be decentralized themselves), emergency response, ramp metering, electronic tolling, traffic signal coordination, and others.

Figure 2-7 and Figure 2-8 provide illustrations of some basic components of regional architectures. Figure 4 depicts a “sausage diagram,” which represents technical elements of the ITS infrastructure and the communications linkages that connect them. The diagram divides the actors into four fundamental subsets: travelers, centers, vehicles, and roadside. Figure 2-8 demonstrates an example of the detail of an architecture document, showing a functional flow diagram for traveler traffic information. Similar functional flow diagrams exist for other subsystems, including freeway control, network surveillance, broadcast travel information, surface street control, and a variety of transit...
operations. Underlying all these diagrams are technical standards and specifications, but the institutional connections they imply are of greater interest to us in this thesis.

Figure 2-7: National ITS Architecture “Sausage Diagram”

The Puget Sound (Seattle) region's ITS architecture will be explored in greater depth in later chapters. For now, it suffices to introduce the basic legal basis, function, and structure of regional architecture, as well as the way in which the architecture fits within the larger process of ITS deployment.

In light of the April 2005 deadline, authors of regional architectures are likely interested in the transition from architecture specifications to deployment and implementation plans. Due to the large, complex nature of Regional ITS Architectures, the large number of connections they prescribe, and the FHWA requirement to use a systems engineering analysis in moving from architecture development to ITS project implementation, DSMs provide a worthwhile and convenient platform for investigation. FHWA has produced several resource documents for ITS planners and program managers that define systems engineering and its relationship to ITS implementation. Appendix A contains the text from FHWA's final rules on Regional ITS Architectures and project implementation.
2.6 The design structure matrix (DSM)

In 1984, Donald Steward introduced the design structure matrix as an analysis tool for complex systems. In the ensuing two decades, researchers in mechanical engineering, systems engineering, and business have modified and expanded DSM manipulation techniques and applications. Analysts typically represent DSMs as a matrix with identically-labeled column and row elements. The elements can be design tasks (activity-based DSMs), working teams (team-based DSMs), or units of a product (component-based DSMs), or parameter decision points (parameter-based DSMs). Common analysis techniques include partitioning, sequencing, and clustering, the latter of which applies most readily to the analysis of Regional ITS Architectures.

In their text *Design Rules*, Harvard Business School Professors Carliss Baldwin and Kim Clark discuss the notion of modularity in design and assembly of products. One of the underlying premises of the text is that designers can gain significant advantages by designing product modules with easy interchangeability between modules rather than by designing stand-alone products. Using the laptop computer as an example, the authors trace the development of computers from their status as rare, cumbersome machines to ubiquitous necessities. They argue that modularity, whereby design of components of the computer are compartmentalized within specialty design groups, facilitated the fast pace of advance in computer design technology. DSMs and clustering readily identify design teams.

DSMs have become powerful tools for analyzing complex system architectures and systems engineering problems, rivaling the capabilities of conventional project management techniques such as the critical path method. Much of the success of the DSM is attributable not only to the ease with which it represents and explains systems but also the ease of modifying and analyzing the matrices themselves. As a result of these analysis procedures, researchers and managers can more easily identify synergies within and between design teams and design activities, opportunities to remove feedback loops in design processes, and opportunities for concurrent engineering and project-time savings.

developed a more rigorous heuristic-based optimization methodology for rearrangement of DSMs into more efficient clusters. Thebeau (2001) presents a modified version of the algorithm that increases the likelihood of finding a globally optimal cost of coordination. Both Fernández and Thebeau allow the user to define various parameters, including a maximum number of clusters and a maximum cluster size.

Most recently, Yu, et al. (2003), suggest a genetic algorithm (GA) for optimal clustering of DSMs. The particular algorithm they describe carries several advantages over the previously-developed algorithms. First, the GA recognizes that, although the DSM is a two-dimensional representation of information flows and communications interfaces, the arrangement of elements is actually three-dimensional. Recognition of this fact leads to identification of clusters within the matrix that, although not evident in an algorithm based on a two-dimensional structure, captures benefits in reality. Secondly, the GA is much more likely to find a globally-optimal matrix coordinating cost than any other existing clustering algorithm. Lastly, the GA can “detect overlapping clusters.” In other words, arrangements that allow elements to be members of more than one cluster can often be more efficient than arrangements that allow only mutually exclusive cluster memberships. To that end, the GA allows some elements to overlap, that is, to “join” more than one cluster. Unfortunately, the algorithm is computationally costly to a point that diminishes its utility.

Chapter 4 covers DSMs and clustering algorithm in greater detail.

2.7 Chapter Summary
Evidence from the literature suggests that the optimal size for metropolitan areas and nations whether from economic, managerial, governing, or sociological perspectives, is not readily computable. Economies of scale encourage larger sizes, but heterogeneity of local preferences limits the extent of growth. As a result, many national governments and, indeed, many metropolitan areas comprise numerous, decentralized jurisdictions, agencies, and other controlling authorities. Yet, except in naturally-occurring, self-organizing phenomena, few complex systems thrive, even if highly decentralized, without some semblance of a central layer of control. Deployment of technology for management of roadways is no different: the technology and infrastructure map closely
to the institutional configurations of the urban regions or states in which the deployment is occurring.

DSMs have a strong foundation in organizational and systems-engineering literature; the legitimacy of the DSM approach is confirmed by its broad application in industrial settings. Given the framework of decentralization in regional transportation management and the need for effective deployment of ITS that both respects existing institutional frameworks and fulfills the need for some degree of centralization, DSMs offer an opportunity for analysis of and improvement in transportation-system management. The aim of this thesis is to explore this possibility.
Chapter 3

Discussion

As the literature review demonstrated, decentralization strategies vary across fields of study and practice. In order to provide a more coherent description of decentralized urban transport, this chapter presents a typology of decentralization and some examples in Section 3.1. Section 3.2 characterizes urban transportation institutions according to this typology and discusses the implications of this characterization.

3.1 Typology of decentralization

Systems exhibiting decentralized characteristics may fall into one or several categories as summarized in Table 3-1. Based on observations of some decentralized systems, categories of decentralization include: spatial or geographic, functional, organizational, computational, and modal.

Decentralization commonly occurs spatially. That is, a system covering a large geographic area, such as a transportation-facility operator, a government, or a corporation, creates sub-systems defined by geography and empowered with specific authorities. The railroad industry is an example of this form of decentralization. Railroad strategists at the UP decided that, as their network expanded, spatial decentralization of management functions would allow for more responsive customer and employee services, better control of vehicle movements and congestion, yet not threaten the integrity of the corporation as a whole. The federalist government of the United States exhibits a spatially-decentralized format for similar reasons, but was not motivated
to “split up” into regions as it expanded; rather, the decentralized components formed into a compact that contained a centralized layer of national government. The disadvantages of maintaining numerous, spatially-decentralized components are similar in both cases: the centralized layer must develop some uniform standards, protocols, or customs for continuity across the entire geography. It must also develop rules for operating at the boundaries of the subsystems. Another disadvantage lies in the potentially costly administration of similar, redundant functions. For example, railroad labor recruiting probably requires similar resources and techniques across the country, yet must be duplicated within each region. In government, each state administers its own public education system, maintains a prison system, builds roads, and carries out many other services in common with other states, yet each has its own bureaucratic system in place for each of these functions. Spatial decentralization of a system such as a government or a railroad must consider the fundamental tradeoff between service quality and cost of administration: at what size is the extra cost to administer locally-tailored railroad services or public schools worth the benefit of local taste and attention? The answer varies among railroad companies and nations, respectively.

Functional decentralization of a complex system can exist independently of other forms of decentralization or along with others, such as spatial decentralization. Consider the previous example of American government, which is spatially decentralized into states, counties, cities, and other levels of authority. At each level, executive branches delegate authority to a variety of functionally-specific agencies and departments: defense, transportation, energy, agriculture, and education, among others, at the federal level; public works, economic development, public safety, and health, among others, at local levels. The US air traffic control (ATC) system is divided into functionally-specific service centers, some of which are in turn divided so as to cover specific geographic pieces of the country. Due to the variety of services provided by ATC, functional separation is convenient for operating the system. It also allows for potentially better performance as centers are able to focus on their particular tasks. On the other hand, functional separation can reduce the ease with which users access services. Residents and business, for instance, often must deal with several functionally-separate, even geographically-separate, agencies when they require the services or permissions of
government. ATC users, likewise, must tune to different radio frequencies for different functions: clearance delivery, ground and ramp control, control tower communications, approach control, in-flight instructions, and information from sources such as ATIS (Automatic Terminal Information Service). In addition, for systems such as air traffic control where safety plays an important role, relationships and communications protocols must be well-defined across different centers for real-time coordination.

Organizational decentralization refers to the decomposition of product components, design teams, or development teams into modules, as described in the text Design Rules by Harvard Business School Professors Kim Clark and Carliss Baldwin. Often, when products are decomposed into tractably-sized subcomponents, the subcomponents are appropriate items around which to build teams of human designers and engineers. The resulting teams can then focus on a single aspect of the larger product, which allows for greater innovation. Furthermore, through DSM analysis and other management techniques, sequential processes can be analyzed to minimize feedback and increase the speed of design or production. Interface rules must accompany such modularization, however, in order to increase the likelihood of (or ensure) interoperability between the subcomponents. An alternative, conceptually-non-decentralized method for product development is “integrated development,” a process that researchers describe roughly as the opposite of modular development. Fully-integrated development requires complete cross-coordination among parts of a product, where parts are elements of the product that have been decomposed into the smallest, simplest components possible. The spectrum of possible arrangements for the design or development process can then range from fully-integrated to modularized. Almost paradoxically, specification of large modules results in more integrated processes within the modules; yet, specification of small modules results in subcomponents whose complexities approaches those of the elemental pieces that accompany full integration. In other words, full integration can be reached ultimately by taking a modularized process and either growing the size of the modules or decreasing the size of the modules.
### Table 3-1: Decentralization typology

<table>
<thead>
<tr>
<th>Dimension</th>
<th>Example</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
</thead>
</table>
| Spatial/Geographic | Railroad industry | • More responsive to customers and employees  
• More appropriate and timely responses to incidents and congestion on the rail network | • Potentially more costly organization of resources  
• Must develop and maintain uniform standards for interoperability  
• Risk suboptimal allocation of network-wide resources |
| Functional      | Air traffic control | • Services provided by ATC vary such that coordination among services is often nonessential  
• Specialization often stimulates better performance within functional groups | • Users require multiple channels for access to information  
• Management of groups can break down in real time emergencies requiring coordination |
| Organizational  | Product design    | • Teams focus on one aspect of a product called a module (organizational specification maps to product specification)  
• Design or production teams are small and manageable | • Risk a lack of interoperability  
• Risk not achieving an “optimal” product |
| Computational   | ITS: Dynamic Traffic Assignment (DTA) | • Faster convergence times for route guidance algorithms  
• System is somewhat redundant and easier to expand | • Likely to find suboptimal, locally optimal, or even inconsistent guidance solutions |
| Modal (Transportation only) | US DOT | • Modal focus induces competition and innovation  
• Clear and distinct financial and budgetary mechanisms | • Efficient inter-modal connections may be de-emphasized  
• Potential redundancy of some administrative functions |

In computational decentralization, a complex problem such as an optimization problem can be distributed across several processors so as to decrease the computational burden on each. Under such configurations, a solution can generally be reached more quickly than with a single processor. Of course, this arrangement is not truly “decentralization” per se, since multiple processors represent more raw computing power...
than a single processor. Nonetheless, absent a single computer with the capability to complete a search algorithm in a reasonable length of time, multiple, parallel processing affords an opportunity for better performance. The possibility exists, however, that distributed computation may also fail to achieve a globally-optimal solution.

Organizing an operation, company, or agency by mode has many of the same advantages and disadvantages as functional decentralization. Air, surface, and marine transport have different characteristics from one another, each of which requires a unique set of policies, analysis tools, and human competencies. As such, the US Department of Transportation (DOT) organizes its primary sub-agencies modally: aviation, highway, railroad, transit, and maritime being the most prominent. A few sub-agencies such as the National Transportation Safety Board perform cross-cutting functions, but the primary policy initiatives at the federal level are derived for each transport mode by its respective administration. A common criticism of this format, while it efficiently focuses "modules" of policy teams on modes for which they have the greatest knowledge, interaction, and experience, is that it decreases the attention paid to intermodal or cross-modal needs and activities. For example, freight is increasingly containerized, which allows for easy transfer from oceangoing ships to trucks to railcars. Passengers in many cities increasingly rely on a combination of pedestrian, auto, bus, and/or rail modes in their daily trips. The physical and operational connections between these modes are often lacking, which perhaps reflects the scarce attention paid to intermodal connections at the policy level. Whatever the case, the tradeoff of a modal focus—or modal decentralization—in a transportation enterprise manifests itself as the conflict between developing and nurturing expertise in policy, planning, and operations for a single mode versus developing connections and synergies among the planners, policymakers, and operators for all modes.

Although these five techniques comprise one typology, they do not represent a mutually exclusive nor collectively exhaustive set of decentralization strategies. Nevertheless, the strategies described within this categorization have implications for urban transportation, in analyzing both existing and desired urban transport systems.
3.2 Urban transportation systems in the decentralization typology

Urban transportation fits into several distinct categories of the typology. The transportation network itself is, for example, modally decentralized because each mode (auto, rail, pedestrian, and others) requires a unique supporting infrastructure. The institutions that control the transport network are decentralized functionally; furthermore, the institutions often fall under the control of political entities that exhibit spatial decentralization. As an example of functional decentralization, consider the roles of two common municipal transportation-related agencies: planning and public works. Planners consider long-term improvements and funding, while public works agencies generally address immediate needs such as street and signage repairs. Each function is handled by a specialized agency. Every American city contains numerous examples of spatial decentralization, from towns to regional and state agencies, regional and metropolitan agencies, and states; each layer of government covers a different swath of territory and population.

Metropolitan areas in the United States exhibit some centralized tendencies. In many cases, cities and towns began as autonomous, centralized units and, as they expanded, adjoined other once-autonomous units. A well-known example of this is New York City, where small villages and town centers on Long Island, Staten Island, Manhattan Island, and the mainland grew toward one another and ultimately formed into the larger cities of Brooklyn, Queens, Staten Island, Manhattan, and the Bronx. As these settlements continued to converge, they ultimately formed yet another compact: New York City. The pattern might be characterized as one of continual re-centralization: the centralized layers gradually grew and merged, along the way acquiring some authority from the smaller, component communities at the peripheries whose growth removed them from isolation. New York is a special case, though, and most cities that experienced similar patterns of growth and centralization did not acquire the same level of authority as New York. As a result, urbanization, even in the New York metropolitan area, tends to reach far beyond the political and organizational limits of a region’s most powerful and centralized component city. The pattern that emerges, then, for urban regions is actually highly decentralized—modally, functionally, spatially, and organizationally—and
generally lacks a strong, single, centralized layer of governance for decision-making or planning transportation services or for many other services.

A centralized layer of control or authority almost always exists even in highly decentralized arrangements of human-organized systems, such as the examples described in the typology and in the literature review (most “self-organizing” systems tend to occur naturally rather than as a result of human constructs). Yet, urban regions lack a centralized control layer for the transportation network. The promise of region-wide ITS deployment is to provide a centralized layer of operations that integrates operators across an entire metropolitan region. Based on the characterization of decentralized systems with central layers that has been developed, there are several key considerations that emerge relating to the creation of ITS architectures:

- Recognizing that urban regions are already highly decentralized, the autonomy of existing sub-components (agencies and political entities) must be addressed, with special attention accorded to the treatment of resource-rich versus resource-poor entities.

- Often, the decentralized characteristics of a complex system emerge when a manager divides it into subcomponents. In developing an ITS architecture, the opposite occurs: centralized characteristics emerge when the managers of subcomponents agree to a centralized configuration. This implies that the degree of authority ceded to the centralized layer will vary from region to region.

- Most urban regions lack a central governance; that is, laws and services vary across the region apart from any unit of government that caters to the entire region (although states sometimes play this role). As a result, the centralized operational layer provided by ITS likely will exist free from an equivalent regional government. In other words, although the ITS architecture and, ultimately, the technologies deployed on the roadway network, may be governed by an agency at some level of government, that level will very likely not correspond to a similar geographic scale as the ITS architecture and the technologies themselves.
Deploying technology requires resource expenditures by all the participating members of the region. To improve the likelihood of success, collaborators should strive to create a strategy for minimizing deployment costs and for sharing costs fairly.

The following chapters present the design structure matrix, or DSM, as a tool for aiding in the process of creating the centralized ITS architecture. Through clustering, the DSM can help to identify arrangements among subcomponents of the region that minimize costs. More broadly, however, the DSM offers a platform for representing clearly and simply the institutions in a region and their relationships, which can supportively accompany the more detailed and complex representations required of ITS architectures.
Chapter 4

Methodology

Metropolitan regions in the United States have undertaken several strategies to integrate and coordinate the functions of their decentralized transportation organizations. Metropolitan Planning Organizations (MPOs), for instance, fulfill regionally-coordinated planning processes that balance the strategic needs of various stakeholders against region-wide financial constraints. Several ITS deployments represent efforts to coordinate day-to-day network operations regionally, such as TRANSCOM, which serves as an information clearinghouse for agencies and decision-makers in the New York City region. More broadly, numerous researchers recognize the increasing need for and movement toward regional integration of agencies for transportation operations (e.g., Briggs, Sussman, Lockwood). Regional ITS Architectures fall within that category of efforts and represent a strategic response to the need for coordination in the deployment of technology to support operations. To date, most of the literature presents a vision of how the integrated systems should look, what problems they should address, and anecdotal case studies of various metropolitan areas’ specific, locally-tailored integration projects and programs. It lacks, however, identification or development of a methodical approach to integration.

The methods presented in this chapter aim to improve the efficiency of technology deployment and the effectiveness of multi-agency coordination in transportation systems through design structure matrix analysis. Efficiency improvements suggests a decrease in the cost of planning, building, utilizing, and maintaining both physical communications
linkages and institutional relationships. *Effectiveness improvements* suggests identification of institutional structures that operate a transportation system better than the structures emerging from existing methods. Under existing methods in Regional ITS Architectures, experts identify desired connections among organizations for building communications channels, coordinating control, and exchanging data based largely on *mutual, pair-wise agreement among the organizations themselves*. The resulting set of connections is a complex network with a potentially-high cost of implementation, little guidance for efficient implementation, and a potentially modest relationship to the transportation network. *DSM clustering results can serve as the basis for new architectures that consider multi-lateral relationships in order to decrease the cost or burden of ITS deployment and improve the effectiveness of system management.*

This chapter is organized as follows. First, we explain the design structure matrix (DSM), clustering algorithms, and how their application to urban transportation organizations can improve the efficiency and effectiveness of Regional ITS Architectures by suggesting new architectures. Specifically, we define five DSMs for clustering analysis. Secondly, we offer several techniques for measuring the connectivity among transportation-related organizations in an urban region based on their physical or travel-demand characteristics. Although we focus exclusively on ITS architectures, the methods and techniques described are extensible to broader, operating architectures, which likely include more stakeholders and higher levels of interaction.

### 4.1 Overview of DSM clustering applied to a Regional ITS Architecture

Methods from several disparate fields converge when developing a DSM for ITS architectures. As such, this section is divided into several subsections, each one addressing a particular component: first, a description of the relevant contents of Regional ITS Architectures; secondly, a description of DSMs and their construction for use in transportation; and finally, a description of several candidate clustering algorithms.

#### 4.1.1 Regional ITS Architectures

A regional architecture generally includes a description of the region, its transportation systems, and stakeholders involved in ITS deployment and systems management.
Furthermore, the document typically specifies “market packages” of ITS technologies relevant to the region. Many of these packages are of modest extent and require little or no organization-to-organization interaction; others, however, require significant interactions. We identify the latter packages and the interactions they imply as exhibiting the greatest opportunity for improved integration through DSM clustering analysis.

*Architecture* refers to the description of linkages between transportation entities; architecture documents generally provide visual layouts of the proposed linkages in the form of directed graphs and flow charts. Textual descriptions support the flow charts and discuss some of the anticipated institutional and physical needs for building relationships and implementing integrated ITS components. For example, the Seattle area’s ITS architecture provides not only a list of suggested connections between regional traffic control centers, but also the following suggestion:

Critical to the deployment of an integrated regional ITS system is the development of electronic interfaces for the full exchange of information and future sharing of ITS devices among the transportation management systems operated by local, county, state, and transit organizations. The acceptance of a standard interface would ease this deployment effort.

The National ITS Architecture prescribes market packages, which “provide an accessible, deployment-oriented perspective... They are tailored to fit—separately or in combination—real world transportation problems and needs.” Examples of market packages include transit vehicle tracking, transit passenger and fare management, transit security, multi-modal coordination, interactive traveler information, electronic toll collection, regional traffic control, railroad operations coordination, weigh-in-motion, international border electronic clearance, emergency response, and incident management system. The National Architecture leaves the task of identifying relevant market packages in specific regions to the regions themselves. Once identified, however, regions also must determine at what scale to apply the market packages. In Seattle, for example, “most market packages do not require interaction with other organizations, and can be generally implemented as stand-alone applications locally.” In other words, in Seattle, most market packages do not require organization-to-organization interaction. Nonetheless, several packages cross jurisdictional lines and invite the establishment of operational concepts, or roles, responsibilities, and relationships among organizations. In
Seattle, consultants identified 9 market packages requiring cross-jurisdictional interaction. These packages are of interest for this work.

Descriptions of the specific required linkages of an operational concept for a market package are found as lists and diagrams in the text of the regional architecture and in its appendices. For instance, Appendix A of the Seattle architecture lists each agency required for deployment of each market package, a list of other institutions with which it should interface, and a description of level and type of interaction desired. Experts suggested seven levels of organization-to-organization interaction for Seattle as follows, in increasing order of importance: consultation, cooperation, coordination, information sharing, control sharing, operations, and maintenance. Maintenance, for example, requires that one organization perform maintenance of another organization’s facilities, an agreement that the architect experts deemed more intense than mere consultation. Five types of organization-to-organization interaction are also defined: video, data, command, request, and status.

An important characteristic of ITS architectures is their reliance on pair-wise connections between organizations. Although some hierarchical relationships exist whereby several organizations or facilities report to a single, common organization, even these relationships are treated as pair-wise. Architectures generally do not recognize opportunities for multi-lateral coordination in real time, tactically, or strategically.

4.1.2 Constructing DSMs

Four DSM categories exist, including component-based, team-based, activity-based, and parameter-based. Analysis of the former two is accomplished best via the method of clustering, while the latter two are analyzed through the methods of sequencing and partitioning. Because ITS architectures describe organizations and their communications linkages, they are best represented using team-based DSMs. The physical transportation network, on the other hand, whose pieces can be broken down into individual components, can be represented best using component-based DSMs. Team-based DSMs contain independent working groups, teams, or organizations as the row and column labels. Entries within the matrix indicate flows of information or communications interfaces between any two teams, with information in the cell flowing from the column-
labeled element to the row-labeled element. In component-based DSMs, the row and column labels are physical elements belonging to a single object, such as parts of an aircraft engine. Entries in the matrix indicate spatial adjacency, energy flows, information flows, or material exchanges between any two elements, with the flow again moving from the column element to the row element.

As a simple illustration, Figure 4-1 contains an example of a team-based DSM for a restaurant. The identically-labeled rows and columns indicate staff teams of a generic restaurant, listed alphabetically: bar staff, cleaning staff, cooks, hosts, managers, owners, valets, and wait staff. In the minute-to-minute and day-to-day operation of a restaurant, information flows from some of these teams to other teams, most frequently through direct verbal communication. An “x” indicates transfer of information from a column entity to a row entity. For instance, in the first column, bar staff send information to cooks when bar customers place food orders, to managers for special customer attention or work-related requests, to valet staff for alerting them of unruly patrons, and to wait staff when tabs and customers are transferred from the bar to the dining area. Although the information flows as represented may not be perfect, the restaurant DSM simply offers an example of the way in which one constructs a team-based DSM.

A few items of particular interest stand out in Figure 4-1. For example, the “managers” team receives information from and sends information to every other team; in other words, the managers experience bi-directional communication with everyone. In

<table>
<thead>
<tr>
<th></th>
<th>Bar Staff</th>
<th>Cleaning Staff</th>
<th>Cooks</th>
<th>Hosts</th>
<th>Managers</th>
<th>Owners</th>
<th>Valet Staff</th>
<th>Wait Staff</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bar Staff</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cleaning Staff</td>
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<td></td>
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<tr>
<td>Cooks</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Hosts</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
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<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Managers</td>
<td>x x x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Owners</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
<td>x</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Valet Staff</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x</td>
</tr>
<tr>
<td>Wait Staff</td>
<td>x</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>x x x</td>
</tr>
</tbody>
</table>

Figure 4-1: Example team-based DSM of a restaurant
DSM literature, such entities are often regarded as integrating teams, system-wide *integrators*, or simply *buses*. Next, the diagonal portion of the matrix is blacked out, indicating that an entity’s relationship with itself offers no meaningful information. Other entries are marked with an “x” to indicate information flow, while pair-wise relationships with no exchange of information are left blank. Typically, for purposes of computation, DSMs represent each “x” and diagonal box as a 1 and each blank as a 0, resulting in a binary numerical representation of flows in the matrix.

Binary numerical representation can be extended to include weighted entries that reflect the importance of a relationship or a particularly large degree of information exchange. In Figure 1, for example, wait staff and cooks exchange large volumes of information intensely and almost continuously: servers deliver order specifications to cooks, and cooks deliver order-status information as well as item-availability information back to the servers. On the other hand, managers and owners communicate infrequently—depending on the particular situation, perhaps as infrequently as several times per month. The varying degree of information-exchange intensity in these two cases can be quantified and represented in the DSM as weighted cell entries. For example, given a relationship between wait staff and cooks of 1, one might judge the intensity of communications between owner and manager to be 0.2. Determination of weighted entries is based on expert evaluation of a system, which may range from arbitrarily-designated weights to more rigorous, objectively-determined weights.

Before manipulating the DSM, it is worth noting that matrix representation of organization-to-organization interactions for transportation purposes in urban regions offers a complete and relatively straightforward alternative to other types of representation. Although not as complete as a regional architecture’s lists, flow charts, and sausage diagrams, the DSM offers much of the same information within a single object.

### 4.1.3 Clustering DSMs

Various algorithms exist for the clustering of DSMs. Clustering, as previously discussed in the literature review, involves rearranging the row and column elements of a matrix in order to identify particularly dense relationships among several elements as “clustered”
boxes along the diagonal. In large, complex, engineering systems, particularly design of complex products, clustering identifies groupings of teams amenable to management and cross-coordination. By recognizing the set of relationships among teams, teams can more readily anticipate and participate in information exchange and communication.

We argue, as others have, that the cost of coordination is smaller for matrix entries when they belong to a cluster than for those same entries when they are unclustered. This assumption is based on the notion that entities can take advantage of economies of scale in the physical construction of connections and/or in the establishment of formal or informal relationships among themselves. Figure 4-2 contains a conceptual illustration of this assumption. On the left side of the figure, five organizations (among a field of potentially many other organizations) with interactions among one another are shown just as they might be shown in an ITS architecture diagram, with only pairwise connections recognized and represented. Clusters emerge through DSM analysis; in this case, it is likely that a clustering algorithm would identify the five organizations as members of a cluster. Recognition of this cluster implies that, rather than each organization pursuing connections with the other four organizations in an ad-hoc manner, all five organizations can commit fewer resources and build a common connection, whether a physical connection or some form of contractual relationship.

Figure 4-2: Conceptual illustration of the efficiency benefit of identifying clusters

The most basic clustering algorithms involve manual manipulation of a matrix. In Figure 4-3, for example, the restaurant DSM has been manually rearranged to
demonstrate clusters of teams with high degrees of intra-cluster information flow and very little extra-cluster information flow. The first cluster includes the bar staff, wait staff, and cooking teams. The second cluster includes the hosts and cleaning staff; this cluster, since it is simply a pair of teams, actually offers less efficiency to the coordination efforts of the group as a whole since both members of the pair would already recognize their mutual information exchange even without clustering. Valet staff and owners belong to no cluster, while managers, as previously discussed, represent a bus (i.e., the management element deals with all other teams and should not be clustered; effectively, the management element belongs to all clusters).

![Figure 4-3: Manually-clustered restaurant DSM](image)

More advanced (than manual) clustering algorithms attempt to optimize the arrangement of the matrix elements by searching for lower-cost solutions to the problem of information exchange. Fernández (1998), for example, approaches the problem of clustering as an optimization problem. In his algorithm, an element is selected at random and accepts bids from all other elements to form a cluster. By assigning a cost to each instance of coordination between two entities, the cost of communication for the entire matrix of entries can be computed. The fundamental assumption driving the formation of clusters is that the cost of coordination is smaller for entries within a cluster than for those same entries if they are unclustered. As the algorithm evaluates cost of coordination for each cluster configuration, it assigns the lowest-cost element to the cluster and continues doing so with other elements until reaching a steady-state cost of coordination. Because this process does not guarantee a global optimum, it deviates from
its search path after reaching a steady state in order to explore other potentially lower-cost arrangements. This process is called simulated annealing. Thebeau (2001) improved the simulated annealing process by forcing the solution back to the prior steady-state solution if, during simulated annealing, the algorithm finds only higher-cost solutions.\textsuperscript{40}

As per Thebeau’s description of the algorithm, coordination cost is calculated as the sum of the cost of intra-cluster coordination and extra-cluster coordination, where intra-cluster coordination is less costly. The equations follow:

\begin{equation}
\text{Intracluster Cost} = [\text{DSM}(j,k) + \text{DSM}(k,j)] \times \text{ClusterSize}(y)^{\text{powcc}} \tag{1}
\end{equation}

\begin{equation}
\text{Extracluster Cost} = [\text{DSM}(j,k) + \text{DSM}(k,j)] \times \text{DSMSize}^{\text{powcc}} \tag{2}
\end{equation}

\begin{equation}
\text{Total Cost} = \sum \text{Intracluster Cost} + \sum \text{Extracluster Cost} \tag{3}
\end{equation}

In the above equations, the cost of an intra-cluster relationship is multiplied by the size of its cluster raised to a power $\text{powcc}$, implying that higher values of the parameter $\text{powcc}$ penalize large cluster sizes. Extra-cluster costs are modeled as a multiple of the dimension of the DSM raised to that the same power, $\text{powcc}$. Since clusters are smaller than DSMs, the extra-cluster cost is larger than the intra-cluster cost for any relationship.

Most recently, Yu, et al. identified several weaknesses with earlier clustering algorithms such as those of Fernández and Thebeau.\textsuperscript{41} In addition to not guaranteeing an optimal solution, the algorithms do not allow clusters to overlap; that is, entities are precluded from belonging to more than one team. They also fail to recognize buses such as the “manager” team in the restaurant example; in such cases, the bus must be identified and removed from the clustering algorithm manually. Lastly, they fail to identify three-dimensional clusters. Because of the two-dimensional representation of entities in a DSM, automated clustering algorithms face difficulty recognizing three-dimensional relationships. Figure 4-4 provides an example of a 3-D DSM. The “third dimension” occurs because entities 1, 2, 3, 7, and 8 comprise a cluster. The cluster, however, is “obscured” by the overlap with other entities and the fact that the cluster spans two corners of the matrix. Yu, et al., present an algorithm that addresses each of these problems.
Yu, et al.’s genetic algorithm is based on the principle of minimum description length (MDL). MDL is a method for representing a set of data with two components: a model of the data and a set of data that do not match the model. The tradeoff is as follows: a long model description leaves fewer mismatched data; on the other hand, a short model description leaves many mismatched data. Since the data description includes both a model description and the mismatched data, the minimum description length trades off detail in the model for more mismatched data. A DSM can be coded as a binary string of ones and zeros (according to a data model), where the string describes some matrix entries and the clusters to which they belong as a data model and other entries as mismatched data. Initially, parent chromosomes of data models are generated and compared with the actual DSM under evaluation; data in the actual DSM that do not match the data model are added to the MDL string as mismatched data. Parent chromosomes can “crossover” with a given probability in order to generate children chromosomes, which may then mutate. The genetic algorithm continues evaluating data-model chromosomes until a certain number of generations have been unable to produce a shorter model description length. The resulting model description, then, represents an optimal set of clusters for the given DSM. Because the search algorithm is path dependent, global optimality is not guaranteed, but can be made more likely if the user specifies a large number of parent and child chromosomes, high probability of crossover, and probability of mutation.
4.1.4 Putting the pieces together

DSMs will be constructed using transportation organizations in an urban region as elements. First, we will construct a binary matrix whose entries reflect the connections as prescribed in the Seattle ITS architecture (e.g., a relationship defined in the architecture is reflected as a 1, and relationships not defined in the architecture are reflected as 0’s). The elements of this matrix will be all the organizations participating in operational concepts for any of the nine identified market packages, effectively all transportation organizations in the Seattle architecture. The second matrix will be the same as the first, except that the entries will be weighed on a scale of 1 through 7 based on the level of organization-to-organization interaction as prescribed by the architecture. For the third and fourth DSMs, we will select rows and columns from the previous two DSMs corresponding only to agencies participating in the “regional traffic control” market package, as this is the largest package with the greatest amount of operating complexity. Fifth, we will construct a DSM of transportation organizations with relationships between them based on physical adjacency and network connectivity rather than on the relationships specified in the Puget Sound Regional ITS Architecture. In all cases, DSMs will be clustered according to the cost-based optimization algorithm developed by Fernández and Thebeau. The genetic algorithm developed by Yu—although by most measures a superior technique—is not publicly available and requires relatively larger computational capacity for the DSMs we consider.

Table 4-1 summarizes the full range of DSMs to be analyzed, including binary and weighted matrices based on given connections by the Puget Sound Regional ITS Architecture; binary and weighted matrices based on given connections only for “regional traffic control” agencies; and binary and weighted matrices based on physical or travel-demand connectivity as determined according to one of three weighing schemes. The latter four are described in Section 4.2.
Table 4-1: Summary of DSMs to be analyzed

<table>
<thead>
<tr>
<th>DSM #</th>
<th>Elements</th>
<th>Source for elements</th>
<th>Source for connections</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Agencies involved in all multi-agency market packages</td>
<td></td>
<td></td>
<td>Binary</td>
</tr>
<tr>
<td>2</td>
<td>Agencies involved in all multi-agency market packages</td>
<td></td>
<td>Puget Sound Regional ITS Architecture</td>
<td>Weighted</td>
</tr>
<tr>
<td>3</td>
<td>Agencies involved in regional traffic control market package only</td>
<td></td>
<td></td>
<td>Binary</td>
</tr>
<tr>
<td>4</td>
<td>Agencies involved in regional traffic control market package only</td>
<td>Puget Sound Regional ITS Architecture</td>
<td></td>
<td>Weighted</td>
</tr>
<tr>
<td>5</td>
<td>Agencies involved in all multi-agency market packages</td>
<td></td>
<td>Infrastructure network and jurisdiction data</td>
<td>Binary</td>
</tr>
<tr>
<td>6</td>
<td>Agencies involved in all multi-agency market packages*</td>
<td></td>
<td></td>
<td>Weighted</td>
</tr>
<tr>
<td>7</td>
<td>Agencies involved in all multi-agency market packages*</td>
<td></td>
<td>Origin-destination flows</td>
<td>Weighted</td>
</tr>
<tr>
<td>8</td>
<td>Agencies involved in all multi-agency market packages*</td>
<td></td>
<td>Flows on links between districts</td>
<td>Weighted</td>
</tr>
</tbody>
</table>

*DSMs for future research

4.2 Weighing DSM entries based on interorganizational connectivity

Some of the methods for representing Regional ITS Architectures as DSMs and for clustering DSMs, as described in Section 4.1, suffer several shortcomings. First, DSMs
representing linkages between organizations as binary lack the more descriptive power of weighted DSM entries. By weighing the entries according to the intensity of communication required between organizations, the clustering algorithm can produce an even more efficient and potentially more effective result. Secondly, the first four DSMs described in Table 4-1 rely entirely on connections prescribed within the ITS architecture document. Those connections are based on the desires of stakeholders (teams) and, to a lesser extent, existing communications patterns and information flows. Clustering them results in efficiency, but not necessarily effectiveness. An independently-produced set of connections may prove more efficient once clustered and, even before clustering, more effective at addressing the actual operational needs of the transportation network. We argue that since the technologies considered for ITS ultimately will be deployed on the transportation network, a sensible prescription of connections would consider the needs of organizations based on the physical connectivity of facilities, adjacency of jurisdictions, and traveler demand for infrastructure across various boundaries.

In this section, we propose several methods for weighing the degree of connectivity between any given pair of organizations providing transportation services on the urban network. First, we consider a weighing scheme that is based on inspection of the proximity of agencies to one another, their degree of overlap, and the interconnectivity of transportation infrastructure between them. Secondly, we propose using origin-destination (OD) data for zones within an urban region to determine the degree of connectivity. Third, due to limitations of OD data, we suggest using traffic volumes across links of the transportation network, such as those obtained from a traditional four-step model, in order to ascertain the degree of connectivity present between any two agencies or jurisdictions.

Using any of these methods, one can quantitatively estimate the degree of effectiveness delivered by a connection between any pair of transportation organizations in a metropolitan area. Next, these measures are used as weights for the entries in a team-based DSM. Finally, by clustering the weighted DSM, a set of clusters may emerge that responds to the actual operational needs of the organizations rather than simply the cost of building communications infrastructure and institutional relationships among a given set of teams and contrived connections. In other words, prescribing ITS
connections based on the physical transportation network may be a more effective way to identify organizational linkages. Finally, clustering this newly-prescribed set of connections may suggest structures for further improving the effectiveness of the regional institutional arrangements.

4.2.1 Weighing interagency connectivity based on physical characteristics

In order to measure the physical connectivity between any two organizations, we first propose to consider their geographic proximity and network connectivity. Intuitively, two agencies with overlapping or bordering jurisdictions will require some form of interaction in order to manage effectively the transportation facilities they share; likewise, two agencies with control of the operations on different segments of a single facility should coordinate their operations tactics and share information in order to operate the system more effectively. Conversely, organizations at opposite ends of a large metropolitan region with few routes in common, no shared boundaries, and no controlling organizations above them in common can reasonably expect to encounter very few, if any, occasions for interacting that will benefit the system's operations.

Organizations typically listed in the communication interface and information flow models of Regional ITS Architectures include city governments and city transportation departments; county governments and county transportation agencies; airports, ports, ferry operators and ferry terminals; state departments of transportation and their regional districts; toll authorities, highway authorities, and special transportation infrastructure districts; transit agencies and operators; metropolitan planning organizations; parking authorities; and other organizations relevant to the deployment, maintenance, or operations of ITS. Each of these organizations encompasses a defined geographic territory and specific transportation facilities such as streets, highways, and transit lines within that territory. These geographic territories may adjoin and overlap one another. The following scheme describes a three-point scale for quantifying the relationship between any two organizations based on their physical characteristics. Because the assignment of points to an organization involves subjective judgment, as does the creation of the scale itself, the resulting matrices should be subjected to sensitivity
analysis in order to detect the influence that the weighing scale (as an input) has on clusters that are formed (as an output).

- Assign a weight of 3 to describe the relationship between a pair of agencies with any of the following characteristics: completely or partially overlapping jurisdictions; shared border for greater than 50% of the border length of one member; shared border for less than 50% of the border length of one member and at least one shared major facility between them.

- Assign a weight of 2 to describe the relationship between a pair of agencies with any of the following characteristics: shared border for less than 50% of the border length of one member; no shared border but a physical separation of fewer than 5 miles and at least one shared major facility between them.

- Assign a weight of 1 to describe the relationship between a pair of agencies with any of the following characteristics: no shared border but a physical separation of fewer than 5 miles; no shared border, a physical separation of 5-10 miles, and at least one shared major facility between them.

- Assign a weight of 0 to describe the relationship between a pair of agencies with any of the following characteristics: no shared border and a physical separation of greater than 10 miles.

- Additional notes:
  - Major facility is defined as an interstate expressway, limited-access highway of 4 lanes or more, grade-separated mass transit line, or Class I freight rail line.
  - Note that “jurisdiction” often implies control over a geographic area and a particular type of infrastructure. For example, “Pleasantville Highway Traffic Control Center” and “Pleasantville Transit” have identical geographic jurisdictions, but the control center does not necessarily come into physical contact with the transit agency. In such cases of jurisdictional overlap without infrastructural connectivity, assign a weight of 1 for the relationship.
After constructing a DSM with the same row and column labels as in Section 4.1, they are populated according to the above criteria. These criteria, although imperfect, approximate the need for coordination among entities based on the physical connectivity of the specific portions of the transportation network for which they are responsible. Finally, using the DSM with weighted entries, we can cluster using the same algorithms as in the binary case. In principle, the clustered result, because of the consideration given to physical connections and the true value of inter-agency connections, will represent a more effective set of connections and arrangement of clusters than those described in the original Regional ITS Architecture. In this thesis, we examine connectivity only with binary descriptions of adjacency and overlap.

4.2.2 Weighing interagency connectivity based on origin-destination demand

Weighing scales based on inspection of physical connectivity inevitably suffer the drawbacks of subjective judgment and arbitrary scaling. In order to ensure greater objectivity and, more importantly, a better reflection of the connectivity between agencies than simply proximity and infrastructural connectivity, we propose an alternative weighing method based on OD data.

OD surveys include data at the level of relatively small zones within metropolitan areas; in the United States, these are typically traffic analysis zones or Census tracts. Data describe the estimated flow of traffic from each origin zone to all the destination zones in the region. Data may include such details as travel mode and trip purpose, but typically only cover the volume of trips for a single day or peak period. Nonetheless, OD surveys provide a detailed picture of the volume and direction of flows among small geographic subsets of a region.

For our purposes, such information could prove valuable as a measure of connectivity between any two agencies in a region. Because transportation operations answer the demands of travelers, the greatest amount of operational effort is likely to be focused on areas of greatest traffic flow. As a result, if large volumes of travelers make trips between zones $A$ and $B$ each day, then it follows that the agency-to-agency interaction requirements between transportation operators covering zones $A$ and $B$ would also be large.
By aggregating OD data to the level of relevant transportation agencies and jurisdictions in a region, we can measure the volume of demand for travel between any two agencies and normalize the demand measure across all pairs of agencies. These normalized values then become weighted entries in the component-based DSMs. The resulting matrix provides a snapshot of the major sources of travel demand between any two agencies or jurisdictions and can be clustered as with the weighted matrices built based on subjective judgments of physical connectivity. The benefits of OD-based weighted entries include a focus on travel demand rather than infrastructure and arbitrary political boundaries and greater objectivity in determining the entries.

4.2.3 Weighing interagency connectivity based on route assignment and link flows across a region

As with the subjective physical connectivity measures, the OD-based measures have a few weaknesses. Foremost, OD data does not include path data; in other words, it tells us origins and destinations but does not describe the path of each traveler on the network. Only by transforming OD data into actual trips with information about route selection can we determine the travel paths and demand across the actual links of the transportation network. We propose such an approach as the most appropriate method for populating a component-based DSM to describe connectivity of agencies in a metropolitan region.

The four-step model, a technique developed for and commonly applied in transportation planning, uses OD data and a description of a transportation network as inputs in order to determine travelers’ selection of modes and routes as outputs. Of interest is the route assignment portion of the four-step model, which describes, often in great detail, the traffic volumes demanded of specific pieces of a transportation facility. Such a description affords us the ability to determine the true connectivity of demand between agencies and jurisdictions.
Figure 4-5: A hypothetical network with links labeled 1-5 and 16-20, divided into subnetworks A, B, and C.

For example, consider a hypothetical network being modeled as depicted in Figure 4-5. The region is subdivided into 3 zones, $A$, $B$, and $C$. Two facilities cross over the borders of the sub-regions and are divided into 10 links, numbered 1 through 5 and 16 through 20. As an output of the four-step model, which will assign OD trips to the links in the route network, we can determine the flows between any two sub-regions, regardless of whether any of that flow originated and/or terminated in either of the sub-regions. For example, if we add the flow that originates on link 1 and travels to link 3 to the flow that originates on link 16 and travels to link 20, we know how much volume traveled between $A$ and $B$, regardless of how many travelers originated at $A$ and/or terminated at $B$.

Coding a transportation network and identifying pairs of network links in order to determine the demand flowing between any pair of sub-regions constitute intensive and tedious efforts. Nonetheless, the approach is feasible and complicated by only several minor issues. For example, some links may terminate at a sub-regional border. Other links that span a border could draw traffic in the model away from perceived origin or destination zones. For instance, a traveler going from link 16 to the portion of link 17 in zone $B$ contributes to the amount of flow between $A$ and $B$. Because 17 spans the border between $A$ and $B$, however, we cannot discern with ease whether travelers exiting at link
17 are, in fact, destined for zone $A$ or zone $B$. In addition, measuring the flows between two mutually-exclusive jurisdictions is straightforward, but measuring flows between two overlapping jurisdictions is not. We can address this problem by measuring the volume flowing from the overlapping to the enclosed jurisdiction and vice versa. Where jurisdictions are exactly or nearly exactly coterminous, another metric should be developed such as counting flows within certain jurisdictions more than once. In spite of these complications, the approach is more intuitively appealing than either the physical connectivity approach or the OD approach for developing the weights in a component-based matrix of a region’s transportation system.

Due to resource constraints, in this thesis we limit ourselves to the less objective, binary, physical infrastructure connectivity approach. Although a rough approximation of the actual physical and travel demand relationships between and among institutions, the approach nonetheless provides a convenient and reasonably accurate process for coding a DSM, and for demonstrating the potential usefulness of clustering.

4.3 Analyzing DSMs for misalignments

Finally, we propose adapting an additional product-design technique for use in transportation. Sosa, Eppinger, and Rowles describe a method for identifying mismatches between product architectures and the products’ corresponding organizational structures.\textsuperscript{42} They compared the clustered product architecture of an aircraft engine’s component-based DSM to the clustered, team-based DSM for managing the design of the same engine and tested various hypotheses to explain the mismatches between the product and management architectures. For example, most physical interfaces in the engine matched an organizational interface among the corresponding design teams. In some cases, however, physical interfaces of two components within the product lacked a corresponding organizational interface between the design teams responsible for those components. Likewise, some organizational interfaces lacked a corresponding physical interface.

The Regional ITS Architecture represents an organizational structure designed to oversee and coordinate the operations of a physical product (the urban transportation network). As with industrial products, the urban transportation system lends itself to
DSM analysis for identification of misalignments between the organizational and physical architectures. Mismatch analysis for an ITS architecture requires two matrices: one of the suggested organizational connections (team-based DSM) and another of the real, physical connections between the facilities in the urban network (component-based DSM). One might propose DSMs 1 through 4 (those based on the Regional ITS Architecture) as approximations of the organizational architecture and DSM 5 (based on the physical connectivity) as an approximation of the physical architecture. These DSMs already have been described. By overlaying an organizational architecture and a physical architecture, mismatches can be identified and described in a straightforward manner. Identifying mismatches can be done automated in a computer spreadsheet, for example, or simply counted manually, although for large DSMs manual counting of mismatches would be tedious. Mismatch identification can be done before clustering, but the exercise is simpler if done after and offers a potentially-revealing contrast.

In industrial design and product development, researchers argue that design processes can be made more efficient and effective by aligning more closely the physical and organizational architectures. Misalignment analysis offers an opportunity to compare directly the architecture described by stakeholder-based Regional ITS Architectures with the architecture based on physical and travel-demand connectivity.

4.4 Chapter Summary

Table 4-1 provides a summary of the DSMs to be developed and clustered. In Chapter 5, we present these DSMs along with the clustered results for each of them using the Fernández/Thebeau algorithm. In Chapter 6, we perform sensitivity analysis and evaluate the results based on efficiency, effectiveness, and feasibility while offering an explanation of methods for misalignment analysis of our results.
Chapter 5

Results

Based on the description of DSM construction and the Fernández/Thebeau clustering algorithm presented in Chapter 4, we analyzed five DSMs: (1) a binary DSM of all organizations associated with market packages in Seattle; (2) a weighted DSM of all organizations; (3) a binary DSM only of organizations associated with the traffic control market package; (4) a weighted DSM of organizations associated with traffic control; (5) and a binary DSM based on the physical connectivity (border sharing and jurisdictional overlap) of organizations. In this chapter, we summarize the results of the clustering analysis with visual displays of the most efficient clustering arrangements as determined by the algorithm. For complete description of the cluster members in each of these cases, refer to Appendix B. Comparison among these outputs, evaluation of their performance according to various metrics, and discussion of the practical implications of clustering (e.g., how to use this information) follow in Chapter 6.

5.1 Binary clustering of all agencies

In this section, we present the results of the binary clustering of the set of organizations identified for interaction. For a complete list of the 67 agencies and jurisdictions—cities, counties, state agencies, and transit operators—in involved in cross-coordinating market packages, refer to Appendix C.

Figure 5-1 depicts all the agencies in the Puget Sound Regional ITS Architecture identified for participation in one or more market packages requiring cross-jurisdictional
interaction. The ordering of elements along the rows and columns is alphabetical by market package (an arbitrary ordering), although the noticeable density of flows toward the bottom right of the figure corresponds to transit agencies. In Figure 5-2, the equivalent information is presented after rearranging the elements of the matrix according to the Fernández/Thebeau algorithm. Limitations are described in Chapter 4, but they merit repeating. Three-dimensional clusters are not recognized; buses must be identified by the analyst prior to running the algorithm; and the result is subject to quantified assumptions such as a penalty for small cluster sizes, penalty for overlapping clusters, and penalty for high numbers of clusters.

![Figure 5-1: Unclustered DSM of information flows between all agencies (67x67)](image)

Figure 5-2 contains the rearranged, clustered version of Figure 5-1: 17 clusters and 12 unclustered entities (alternatively interpreted as clusters with just one entity). Prior to clustering, we identified two of the elements as buses: King County and the Northwest District of the Washington State Department of Transportation (WSDOT NW). Although neither communicates with every other member of the matrix, both communicate with a majority of the members and with members of nearly all 17 clusters.
The 17 clusters have sizes of 2 members (6 clusters), 3 members (7 clusters), and 1 cluster each with 4, 5, 7, or 8 members. The arrangement of entries off the diagonal, outside the clusters indicates a relatively large amount of extra-cluster communication, which suggests that, at least for some cluster members, the benefit of joining a cluster may be modest. On the other hand, additional buses can be identified and removed for further analysis.

### 5.2 Weighted clustering of all agencies

Next, we consider the same connections as in Section 5.1, except that entries are weighted based on the intensity of communications between elements. The unclustered matrix of weighted entries appears in Figure 5-3. As discussed in the methodology chapter, weights range from 1-7, corresponding to the seven levels of organization-to-organization interaction specified in the Puget Sound Regional ITS Architecture. Figure 5-3 is identical to Figure 5-1, except that thicker bullets indicate more intense existing or planned communications, while thinner bullets represent less intense communications or those linkages that are identified by the architecture merely as “potential.”
In Figure 5-4, we see the clustered arrangement of the weighted entries. In this case, we observe the same twelve unclustered elements as before, including the 2 buses. We also observe three 2-member clusters, three 3-member clusters, three 4-member clusters, two 5-member clusters, and two 7-member clusters. Although some entries remain off-diagonal, many of the more heavily-weighted entries have remained within clusters.
5.3 Binary clustering of traffic control agencies

The next set of results stems from clustering of agency communications flows required only for the “regional traffic control” market package. The architecture specifies several dozen local traffic control centers and several county traffic control centers, while recognizing the current existence and operation of a WSDOT NW-operated control center. Traditionally, control centers engage in activities ranging from real-time traffic signal adjustment to monitoring the road network for incidents and congestion, warning drivers about and directing them around incidents and congestion through various mechanisms (such as VMS), and dispatching emergency responders. As discussed in the literature review, however, advanced ITS applications currently under development may someday complement these roles of traffic control centers, including dynamic route guidance and signal control. Figure 5-5 depicts the flows of information as envisioned by the Puget Sound Regional ITS Architecture among control and management centers involved in regional traffic control.
Figure 5-5: Unclustered DSM of binary communication flows between traffic control agencies (45x45)

Figure 5-6 shows the clustered result of the traffic control agencies based on binary representation of communication flows among them. King County and WSDOT NW remain as buses in this DSM and are unclustered (both are identified by arrows in Figure 5-6). This arrangement also includes 12 additional unclustered elements and 7 clusters each with a pair of members. Only 4 clusters contain more than a pair, including three clusters with 3 members and one cluster with 8 members. Although this cluster could be improved via manual manipulation and identification of overlapping clusters, its results under the baseline parameters nonetheless suggest room for improvement.
5.4 Weighted clustering of traffic control agencies

The analysis of weighted DSMs for the agencies participating in regional traffic control closely mirrors that of the analysis for the binary case, except that, as with the previous weighted analysis, entries range from 1 to 7 based on the level of organization-to-organization interaction specified by the architecture. Figure 5-7 represents an unclustered arrangement of elements, while Figure 5-8 represents a clustered arrangement of the same information.
Figure 5-7: Unclustered DSM of weighted communication flow for regional traffic control

Figure 5-8: Clustered DSM of weighted connections for regional traffic control
5.5 Binary clustering of agencies based on physical connectivity

As discussed in Chapter 4, clustering DSMs by any algorithm has the potential to improve the efficiency of existing institutional structures of Regional ITS Architectures unambiguously; effectiveness improvements are less direct. Nonetheless, we can also use wholly new criteria to define linkages among agencies other than stakeholder agreement. Specifically, we can prescribe linkages based on their physical connectivity. Figure 5-9 presents such a DSM, where we use physical adjacency or jurisdictional overlap of various agencies as an indication that an organizational linkage should also exist. Since the linkages are represented as binary entries in the matrix, relationships among organizations are prescribed only when they are adjacent or share territory.

![Unclustered binary DSM of physical connectivity (63x63)](image)

Figure 5-9: Unclustered binary DSM of physical connectivity (63x63)

Figure 5-10 presents the result of clustering the physical DSM. In this case, we specified 5 buses: King County, WSDOT NW, Sound Transit, Sound Transit’s Regional Express bus service, and King County Metro transit service. Among the other entries in the matrix, the majority fit into clusters along the diagonal, especially as compared to other DSMs analyzed for Seattle’s ITS architecture. Twelve clusters contain just two members, while two contain 3 members, and three contain 6 or more members. Due to
the construction method for this DSM, the clusters generally consist of elements that are geographically proximate to one another.

Whatever the interpretation, we also note that clustered DSMs in all the cases explored in this chapter can be further improved through manual manipulation, forcing overlap of some clusters, and re-evaluation of extra-cluster linkages.

![Figure 5-10: Clustered binary DSM of physical connectivity (63x63)](image)

Chapter 6 discusses these results in several contexts. First, we present sensitivity analysis for the DSM clustering. Next, we evaluate clustering performance against several pre-defined metrics, both numeric and qualitative, and suggest criteria for assessing the relative values of clustered outcomes. Finally, we offer guidance for interpreting the meaning and usefulness of clustered DSMs for a region.
Chapter 6

Evaluation

Having demonstrated DSM representation and clustering of decentralized urban transportation organizations, we now evaluate the validity, quality, and usefulness of the results.

In order to evaluate the validity of the results, several dimensions of sensitivity analyses of DSM clustering are suggested and described. Quality of results is measured according to three metrics: efficiency, effectiveness, and feasibility. We also compare effectiveness and efficiency of two types of DSMs using misalignment analysis. This chapter also explores the practical implications of clustering by considering how a regional leader might use a clustered DSM for urban transportation to reduce technology implementation costs, strengthen institutional relationships, improve transportation system performance, or simply catalyze deployment of integrated operations. Finally, we discuss complicating issues such as conflicting temporal scales of operation among organizations, conflicting missions, hierarchical relationships, and creation of new organizations.

6.1 Sensitivity analysis

There are several dimensions on which one can perform sensitivity analysis of DSM clustering results such as those presented in Chapter 5. First, the clustering algorithm chosen and demonstrated in this thesis suffers the fundamental shortcoming that its path dependency precludes it from achieving a globally-optimum coordination cost for a given
matrix. The number of possible arrangements of elements in a DSM is \( n! \), where \( n \) is the number of elements. For our smallest matrix, 45x45, this results in \( 1.20 \times 10^{56} \) possible arrangements. Because the algorithm does not search all possible arrangements, but instead only a subset, it often suggests varying solutions when run many times; therefore, it should be run repeatedly in order to find a minimum cost result that has a higher likelihood of being a global optimum. Secondly, the input parameters to the algorithm allow the user to weigh variably the value of small versus large clusters, large numbers versus small numbers of clusters, and several other conditions of the clustered matrix.

Third, for weighted DSMs, the weights used to reflect communications intensity between organizations in the matrix are somewhat subjective, although based in our case on a description of levels of communication specified by Seattle’s Regional ITS Architecture. Nonetheless, we should attempt to cluster the matrix using variations on the weighing scheme in order to measure its effect on the results. Lastly, the choices of the elements themselves require up-front judgment as to the importance of certain stakeholders’ participation in the architecture and the commensurability of temporal scales of communication flows between organizations. In order to test the sensitivity of the results to the inclusion of elements in the DSM, several cases should be considered, some with and some without organizations whose membership is of questionable relevance. In this thesis, we consider only the first two dimensions of sensitivity analysis and leave the latter two for further research.

Instead, we present sensitivity analyses on the first two dimensions using two of the five matrices clustered in Chapter 5: number 4 (weighted traffic control DSM) and number 5 (binary physical connectivity DSM). Selection of these two matrices for sensitivity analysis is somewhat arbitrary, but together they capture important characteristics that cover all 5 DSMs: we consider both a binary and a weighted DSM in our sensitivity analyses; in addition, we consider a DSM constructed from the given, architecture-prescribed connections as well as one constructed based on our measures of physical connectivity.

As per Thebeau’s description of the algorithm, coordination cost is calculated as the sum of the cost of intra-cluster coordination and extra-cluster coordination, where intra-cluster coordination is less costly. The equations follow:
Intracluster Cost = \([DSM(j,k) + DSM(k,j)] \times \text{ClusterSize}(y)^{\text{powcc}}\)  \(1\)

Extracecluster Cost = \([DSM(j,k) + DSM(k,j)] \times \text{DSMSize}^{\text{powcc}}\) \(2\)

Total Cost = \(\sum \text{Intracluster Cost} + \sum \text{Extracecluster Cost}\) \(3\)

In the above equations, the cost of an intra-cluster relationship is multiplied by the size of its cluster raised to a power \(\text{powcc}\); higher values of the parameter \(\text{powcc}\) penalize large cluster sizes. Extra-cluster costs are modeled as a multiple of the dimension of the DSM raised to that power, \(\text{powcc}\). Since the size of clusters, by definition, is less than or equal to the size of DSMs, the extra-cluster cost is larger than the intra-cluster cost for any relationship. Costs are summed over all entries to determine total coordination cost.

Table 6-1: Sensitivity analysis of DSM #4

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<th>Final cost</th>
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<td>271.0</td>
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Table 6-1 summarizes the final coordination cost achieved in 25 runs for DSM #4. As the table shows, the costs differ from one run to another. Since we are interested more in cluster membership than coordination cost, however, the implications of these variable results in the case of DSM #4 are relatively minor; that is, cluster membership varies very little in most runs even though the measure of coordination cost changes noticeably. In DSM #5 (see Table 6-2), on the other hand, the final clustering arrangements often bear little resemblance to the minimum-cost arrangement (run 15).

The consequences of these types of changes are important in analyzing DSMs for transportation. The results imply that multiple clustering runs are advisable; a single run is unlikely to find a useful result. Although there is no guarantee of finding an optimal result even by performing multiple clusterings of a DSM, the likelihood of finding a lower-cost solution with more runs certainly increases. With modern computing power and modestly-sized DSMs (Pentium M 1.6 GHz Processor performed each run in less than 1 minute), this task is certainly feasible.
Table 6-2: Sensitivity analysis of DSM #5

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<td></td>
<td>13</td>
<td>994.1</td>
<td>418.9</td>
<td></td>
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<tr>
<td></td>
<td>14</td>
<td>1298.0</td>
<td>115.0</td>
<td></td>
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<tr>
<td></td>
<td>15</td>
<td>854.2</td>
<td>558.8</td>
<td></td>
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<tr>
<td></td>
<td>16</td>
<td>1055.0</td>
<td>358.0</td>
<td></td>
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<tr>
<td></td>
<td>17</td>
<td>1004.0</td>
<td>409.0</td>
<td></td>
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<tr>
<td></td>
<td>18</td>
<td>898.0</td>
<td>515.0</td>
<td></td>
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<tr>
<td></td>
<td>19</td>
<td>1198.0</td>
<td>215.0</td>
<td></td>
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<tr>
<td></td>
<td>20</td>
<td>885.3</td>
<td>527.7</td>
<td></td>
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<tr>
<td></td>
<td>21</td>
<td>1035.0</td>
<td>378.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>22</td>
<td>1034.0</td>
<td>379.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>23</td>
<td>1068.0</td>
<td>345.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>918.0</td>
<td>495.0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>25</td>
<td>930.3</td>
<td>482.7</td>
<td></td>
</tr>
<tr>
<td><strong>average</strong></td>
<td></td>
<td>1056.8</td>
<td>356.2</td>
<td></td>
</tr>
<tr>
<td><strong>std dev</strong></td>
<td></td>
<td>132.8</td>
<td>132.8</td>
<td></td>
</tr>
<tr>
<td><strong>max</strong></td>
<td></td>
<td>1393.0</td>
<td>558.8</td>
<td></td>
</tr>
<tr>
<td><strong>min</strong></td>
<td></td>
<td>854.2</td>
<td>20.0</td>
<td></td>
</tr>
</tbody>
</table>

One difficult question an analyst faces is which clustering result do we choose?. Unless the user is interested purely in efficiency, in which case the least-cost DSM is most appropriate, other criteria should be considered. These are discussed in Section 6.2.

Next, we analyze some of our DSM clustering results for sensitivity to the powcc parameter. As reflected in Equations 1 and 2, powcc trades off cluster size against the number of clusters in a DSM. As a result, the choice of exponent for powcc determines whether the algorithm will be "biased" toward a large number of small clusters or a small number of large clusters. To measure the impact, we compared the resulting cluster memberships of DSM #4, where powcc was 1, with the memberships after 10 runs with powcc set to 2. The lowest-cost result's cluster members matched 75% of those in the
case with $powcc$ set to 1. We repeated the process for DSM #5 and found only a 50% match in the lowest-cost case. As expected, the case with the higher-valued exponent produced many more small clusters (particularly those with membership of fewer than 4 organizations). The results for DSMs 4 and 5 both suggest a relatively strong sensitivity to the variable $powcc$, and imply that any clustering analysis with this algorithm should examine the impact of changes in the variable in case more desirable arrangements emerge under a different $powcc$ setting.

Thebeau recommends setting $powcc$ to 1, but reached this conclusion based on analysis of one DSM for elevator design. No doubt, a $powcc$ of 1 would be a good starting point, but analysts should increase the value of the exponent as high as 2 if they desire relatively smaller clusters and decrease the value of the exponent as low as 0.5 if they desire relatively larger clusters. Smaller clusters may be advantageous in regions with powerful organizations, while larger clusters may be advantageous for resource-poor organizations.

This section has demonstrated results of two dimensions of sensitivity analysis to consider when evaluating a clustered DSM result. Other algorithms, such as the one developed by Yu, et al., provide a better likelihood of reaching a globally-optimal arrangement (thereby reducing the need for sensitivity analysis of the first and third types presented) at the expense of longer computation times. If the Yu algorithm is available and achieves results in modest amounts of computation time, it is a more advisable method for clustering because it avoids the need for extensive sensitivity analysis.

### 6.2 Evaluation metrics

Having performed DSM clustering and sensitivity analysis for a variety of matrix types, we now venture to determine which clustered DSMs represent the “preferred” arrangement. In this section, we present several criteria for judging the value of a clustered DSM: efficiency, effectiveness, and feasibility.

#### 6.2.1 Efficiency

_Efficiency improvements_ suggests a decrease in the cost of planning, building, and maintaining both physical communications linkages and institutional relationships. In
other words, a process that reduces the financial or time burden—so as to allow an organization to carry out a prescribed set of tasks more easily—represents a more efficient process. In DSM clustering, we assume that intra-cluster tasks and communications are less costly and less burdensome to an organization than extra-cluster tasks. Having already discussed the logic and quantitative computation of this relationship, we present a summary of the cost reductions for the best-performing run of each of the 5 DSM types in Table 6-3. We note, however, that comparing efficiency measures across DSMs is not valid because of the varying dimensions, starting costs, and weights of the DSMs. Furthermore, the percentage improvement in cost has little meaning since it depends on the starting cost, which is a function of the arbitrary ordering of matrix elements.

<table>
<thead>
<tr>
<th>DSM #</th>
<th>Description</th>
<th>Starting cost</th>
<th>Best ending cost</th>
<th>Best cost improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Binary, all organizations</td>
<td>146.8</td>
<td>90.2</td>
<td>39%</td>
</tr>
<tr>
<td>2</td>
<td>Weighted, all organizations</td>
<td>263.1</td>
<td>131.9</td>
<td>50%</td>
</tr>
<tr>
<td>3</td>
<td>Binary, traffic control</td>
<td>3109</td>
<td>1543</td>
<td>50%</td>
</tr>
<tr>
<td>4</td>
<td>Weighted, traffic control</td>
<td>504.3</td>
<td>128.8</td>
<td>74%</td>
</tr>
<tr>
<td>5</td>
<td>Binary, physical connectivity</td>
<td>1413</td>
<td>854.2</td>
<td>40%</td>
</tr>
</tbody>
</table>

Since we are more interested in the arrangement of clusters than coordination cost as a metric used to arrive at a clustered DSM, a more direct gauge of efficiency is to analyze the number of entries that belongs to clusters versus the number that does not. For example, in the clustered version DSM #4, there are 47 clustered entries and 22 unclustered entries (not including diagonal entries or entries associated with a bus). In the clustered version of DSM #5, there are 144 clustered entries and 200 unclustered entries. This analysis provides a method and a much more directly applicable metric for DSM analysts in a particular region to determine the usefulness of various clustering arrangements.
6.2.2 Effectiveness

Effectiveness improvements suggests that DSM analysis methods produce institutional structures that operate a transportation system better than the structures emerging from existing methods. Effectiveness is more ambiguous to measure than efficiency for DSMs, but we propose several approaches for comparing clustered versus unclustered architectures.

First, the clustered versions of DSMs 1 through 5 are all more effective than the unclustered versions because they suggest organizational structures that capture the benefits of multi-lateral communications. Recognition of such structures could lead to faster real-time responses to network needs as well as tactical and strategic decisions that account for the needs of a wider variety of organizations. Measuring effectiveness in this sense is not straightforward and not necessarily quantifiable; rather, it requires accounting of the clusters and their members. If clustering identifies several or more clusters, each with several members and, as with measuring efficiency, captures inter-organization interactions inside rather than outside of clusters, then the result can be the basis for a more effective architecture than an unclustered DSM. By virtue of recognizing multi-lateral relationships and capturing interactions within teams, where many decisions can be made more judiciously and expeditiously, clustered DSMs are more effective. Given some limit to cluster size, clustered DSMs with increasing numbers of interactions captured within clusters are increasingly effective; conversely, clustered DSMs with few clusters or with many entries outside of clusters have less potential to provide the basis for effective architectures.

Other, more direct methods of detecting effectiveness include measuring reduction in travel time, incident response times, and accident rates; unfortunately, performing such experiments would be unrealistic and attributing changes in performance to the clustered architecture would be unclear in any case. Another method of measuring the effectiveness of a clustered architecture is to measure the speed with which technology is deployed on the network before and after implementation of a clustered architecture. This suffers some of the same drawbacks as the previous method, but measuring deployment progress could be more easily attributed to architectural improvements. A final method for measuring effectiveness is to generate and evaluate hypothetical
scenarios and consider the performance of the transportation system under unclustered and clustered architectures. One such scenario is presented next.

On the afternoon of Tuesday, February 1, 2005, several weeks after one of New England’s largest snowfalls, traffic on the streets and highways of downtown Boston stood still. Gridlock gripped Interstate 93, the major north-south expressway and the route which passes through the notorious Big Dig; several major arterials south of the financial district, including Columbia Road, Massachusetts Avenue, Dorchester Avenue, and Southampton Street; major arterials crossing the Charles River into Cambridge including Massachusetts Avenue at the Harvard Bridge and Cambridge Street at the Longfellow Bridge; and most of the major arterials serving downtown neighborhoods. Residents and local media demanded accountability from public officials, who proceeded to pass blame among themselves. Two days after the incident, a group of transportation-agency officials convened to discuss the matter, diagnose the problem, and attempt to improve the conditions that led to the gridlock. Although no single cause was ever identified publicly, some officials offered that the congestion stemmed from several incidents and, perhaps, some bad fortune: a Massachusetts Highway Department crew repairing potholes on Interstate 93, an electric utility crew from N-Star performing routine repairs on an arterial, leftover snow restricting roadway capacity in most places, and traffic signal failure at a major expressway-arterial interchange. Whatever the actual causes, gridlock severely restricted mobility of Boston drivers for several hours, and the response by officials was sluggish. According to the Boston Globe:

“[Boston Transportation Department Deputy Commissioner Tom] Tinlin said agencies did not tell one another quickly enough about problems such as traffic signal malfunctions and backups on feeder roads leading to Interstate 93. No agency, however, accepted blame yesterday, and no one apologized to commuters.”

The follow-up meeting of officials included representatives from the Massachusetts Turnpike Authority, Mass Highway, Boston Transportation Department (BTD), Massachusetts Department of Conservation and Recreation
(DCR), and local and state police. The meeting resulted in a plan for avoiding future incidents by "starting hourly communication between agencies, closely monitoring six trouble spots, and stationing more police officers at those choke points." Our question is this: how could a clustered architecture, whether for ITS or operations more generally, have helped this situation?

Unclustered DSM representation of Boston transportation organizations and their communication flows would have allowed identification only of pair-wise and hierarchical communications. By clustering the DSM, a structure could have been revealed that indicated a strong multi-lateral flow of information among Mass Highway, Mass Turnpike, BTD, and DCR. Particularly if based on physical connectivity, since much of the congestion spilled over from one facility to adjacent facilities, the DSM would recognize the overlap of network links and the density of flows between organizations, and would likely suggest that the organizations cluster.

Prior to the congestion incident, officials of these organizations doubtless recognized that they share transportation responsibilities with others in the region; yet, evidence shows that outside of special events such as the Democratic National Convention (DNC), the impetus to interact multi-laterally among this subset of regional organizations was lacking. Clustering highlights dense, multi-lateral interactions and provides regional leaders and organizations a perspective on how they fit within the broader picture, which in this case would perhaps have resulted in a formal, prevention-minded organizational structure shared among several organizations or, at least, knowledge among the stakeholders of who their most important contacts would be in developing a real-time strategy for responding to the congestion.

Although measuring the impact of clustering on transportation effectiveness quantitatively is difficult, we can nonetheless gauge effectiveness qualitatively. For example, since clustering identifies multi-lateral relationships that make communications more efficient, we can deduce that the operational effectiveness of the involved organizations is also more effective. In other words, facilitating the speed and efficiency of communications among organizations also improves their ability to perform functions effectively. Scenario planning is a specific example of applying the insights of clustering
to transportation organizations in order to improve the long-term ability of the organizations to respond to operational issues more effectively. In Boston, for instance, clustering could have identified the organizations necessary for participation in scenario planning efforts to prevent and/or respond to incidents such as extreme congestion and special events such as the DNC.

6.2.3 Feasibility

*Feasibility*, often closely related to effectiveness, in our case refers to stakeholder acceptance of an institutional architecture. For example, the Puget Sound Regional ITS Architecture had to gain considerable stakeholder acceptance in order to be completed. As a result, the DSMs that represent information flows as defined in the architecture presumably would be highly acceptable to the stakeholders represented on them. Since clustering in and of itself does not change any of the entries in the matrix, a clustered DSM of already agreed-upon connections also presumably would be acceptable. If the clustered DSM is used to justify the creation of new organizations, as will be discussed in the next section, it may be less well-received. DSM #5, based on physical connectivity, shares some connections in common with the other DSMs, but because its creation was done simply by the author, we have little knowledge of its feasibility in terms of stakeholder acceptance. Ali Mostashari (2005) presents a stakeholder-based process for representing complex systems such as transportation systems, some of the insights of which would certainly benefit regional organizations interested in developing or analyzing new architectures.44

6.2.4 Misalignment analysis

Once a process for coding the physical network and/or travel-demand connectivity into a DSM is completed, we can compare the physical architecture to the organizational architecture as described in Chapter 4 and demonstrated by Sosa, Eppinger, and Rowles.45 This comparison allows for identification of mismatches between the physical and organizational domains, which can thereby suggest institutional changes to match the physical architecture more closely and potentially improve system management.
Comparison of the cluster members of the lowest-cost clustered version of DSM #4 with the lowest-cost clustered version of DSM #5 provides an approximate measure of the mismatch between the organizational and physical architectures. We see that 50% of the organizations belong to the same cluster as at least 1 other organization in both DSM #4 and DSM #5. This suggests a significant mismatch, confirming our hypothesis that a DSM based on physical connections will differ from one based on other criteria, such as mutual pair-wise stakeholder agreement in Regional ITS Architectures.

6.3 Practical implications of DSM clustering

Having performed clustering, sensitivity analysis of the results, comparison of the results with one another using performance metrics, and mismatch analysis, a regional transportation leader or agency will still ask how to use the information. In other words, given a clustered DSM of regional transportation organizations that we believe provide more efficient and effective bases for architecture, what does the region do next? We present in this section strategies for applying the insights offered by DSMs and clustering to a regional transportation system’s institutional environment. First, we survey the application of clustering in other fields. Next, we discuss two categories in which clustering may be helpful.

In other fields, the application of clustering can imply real changes for an organization. For example, in product design, clustered DSMs identify teams into which specific elements (e.g., design groups) can join. These structured teams hold fewer meetings with more participants to discuss issues since the interactions among their component groups are far more regular than interactions with other groups. In principle, the design process will proceed faster and produce better design since communications occur more efficiently. If the organizational architecture maps well to the physical architecture of the product, the design will be more effective, whereas situations with considerable mismatch between organizational and product architectures may be less effective.46

In transportation, there are two categories in which a region may wish to apply clustering. First, it can be applied simply as a catalyst for efficient deployment of technology. One of the barriers to ITS deployment is institutional cooperation and
development of agreements for cost- and responsibility-sharing. Clusters can identify teams of organizations that should work together in early deployment stages. Secondly, DSM clustering can be used to identify and establish an arrangement of organizations to improve the effectiveness of operations.

Taking advantage of the efficiency gains resulting from a clustered arrangement of organizations can serve as a catalyst for technology deployment in contexts where connections required among agencies may otherwise not be realized. The ad-hoc nature of ITS architectures places a significant implementation burden on each organization to develop formal relationships with other organizations and to devote financial and human resources to building connections to those other organizations. By identifying clusters in a DSM, a subset of regional organizations can reduce its cost of implementation and pool its resources in order to deploy technology more quickly and inexpensively.

In the longer term, DSM clustering can serve several possible functions: identification of new organizations, identification of effective arrangements of organizations for operations, and as a tool for scenario planning. Clusters represent organizational structures at the sub-regional level and allow decentralized actors to recognize their dense interactions. One could then think of a cluster as a “natural” organization whose scale lies between that of an individual organization and the entire region. Because individual organizations often exist as mere historical legacies and without any current operability, a cluster can adjust for the inefficiencies and potential operational ineffectiveness of their coincident structures by pointing toward a new structure that combines several previously un-integrated entities.

At one extreme, a cluster merely suggests a set of organizations to which all the members should devote resources to build informal, multi-lateral relationships. At another extreme, a cluster may suggest outright consolidation of its several members. In between, a number of options ranging from relationship-building to more formal integration exist for members of a cluster:

- Members can establish an informal coordination structure that specifies periodic meetings of key individuals.
- Members can jointly develop, build, and maintain the physical communications linkages among them.
• Members can establish a common repository for data including special events, real-time conditions, or scheduling of network services such as transit schedules or maintenance and repair schedules.

• Members can formalize their relationship through a multi-lateral program of roles and responsibilities for sharing control of the physical network and coordinating operations and maintenance.

• Members can use their unique cluster relationship to perform scenario planning for special events such as the DNC or sporting events, crises such as a terrorist attack, or response to extreme weather conditions such as a blizzard or hurricane.

Fernández emphasizes that careful consideration should be accorded to the matrix entries that lie outside of clusters. Although the intra-cluster members can enjoy efficiency and/or effectiveness benefits by pursuing integration of some sort as described above, occasionally an extra-cluster communication flow of great importance exists. Fernández suggests that, prior to implementing any strategies stemming from the identification of clusters, the extra-cluster relationships be analyzed to determine whether they are expendable or not. Extra-cluster relationships with little operational consequence are ideal candidates for removal from the institutional architecture. On the other hand, extra-cluster relationships between two organizations with high operational importance or stakeholder value should be evaluated to see if the relationship fits better inside the cluster of one of its corresponding organizations.

The particular response of a region to the identification of clusters within either a predetermined or newly-defined collection of communication flows depends on the preferences of the stakeholders involved. Conceivably, consolidation may emerge as a preferred approach in many cases, particularly where the cluster contains small organizations with fewer resources and less political power. For example, far-flung suburbs of Seattle may find advantages in consolidating their traffic control functions, especially since dense communications already exist among them. On the other hand, a clustered arrangement of large, well-established agencies such as WSDOT NW, the city of Seattle, and other inner suburbs may be, for political reasons, less inclined to consolidate; nonetheless, they may recognize the value of integrating some aspects of their operations, particularly when clustering highlights that dense multi-lateral
relationships already exist. The lack of multi-lateral response by Boston agencies to a “perfect storm” of congestion exemplifies an instance when identification of clusters could facilitate some form of integration, either for strategic, scenario-planning purposes or for tactical response.

Whatever approaches a region ultimately decides to pursue, even if leaders determine that there is insufficient benefit from clustering altogether, the DSM representation affords a convenient platform for exploring alternatives with the potential to decrease technology deployment costs, speed the pace of deployment, increase the effectiveness of operations, and improve the ability of organizations to make better plans for responses to future crises.

6.4 Complicating issues

This section identifies four issues that complicate or are complicated by DSM clustering: differing temporal scales of operation among participating organizations in a region, the mismatch among the roles and missions of organizations sharing space in a DSM, the question of hierarchy and chain of command among organizations, and the emergence of new organizations to manage operations.

First, temporal scales often differ among agencies. City, county, and state departments of transportation or public works, for example, perform transportation functions ranging from real-time signal control to tactical maintenance scheduling and planning to longer-term capital planning. On the other hand, emergency response agencies such as fire and police (often operating as departments of cities, counties, and states) devote a dominant share of their resources to real-time response. Recognizing that agencies’ responsibilities span a variety of time horizons can affect the choice of whether or not to include some of them in a DSM. For example, should a police dispatch center and a traffic-control center be represented together in a DSM? Probably so. Should a police dispatch center and a transit agency’s fare planning division be represented together? Probably not. In this thesis, we have explored at a relatively high level the interactions among agencies. For instance, cities are represented in the traffic-control DSM alongside other entities who deal with traffic control such as WSDOT-NW and King County. We do not, however, represent DSMs at the more intricately-detailed level.
of city departments (e.g., public works, police, and fire) and transit agency divisions (e.g., control center operations, strategic planning, and labor relations). Because our DSMs represent interactions among larger agencies, the distinction between temporal scales is less important; cities, counties, transit agencies, and state DOTs include some aspects that deal with real-time issues, and our DSM encapsulates them by simply representing the entire organization as an element. In more detailed analyses, however, recognizing the various time-scales for distinct types of information flow (real-time versus tactical versus strategic) affects DSM representation.

In addition to temporal scale, mismatches among transportation organizations’ missions or roles often exist. Consider a public works agency, for instance, whose responsibilities include routine roadway repairs and maintenance of infrastructure. Within the same municipal government, perhaps even within the same transportation department, another working group may have exclusive responsibility for maintenance of traffic signals or signage. Although the functions of such groups are likely coordinated within the department, they are probably not coordinated with other organizations. In building a DSM, one must consider whether the missions of various organizations share anything in common, lest that affect their inclusion within a particular DSM. Of course, the flow of information among organizations primarily should determine whether or not one includes it in the DSM, but consideration of its mission and the purpose of the particular DSM may in some cases warrant removal of an element from a matrix. In our analysis, for example, the “ITS data backbone” for Seattle was removed from the matrices for evaluation, not because of a lack of information flow to and from it, but because the backbone did not have a mission of real-time or tactical traffic control like the other organizations represented. It was mismatched both temporally and based on it mission.

In many contexts, organizations in a regional transportation system control or are subordinate to other organizations. Some organizations derive their authority from legislative declarations (transit agencies and port authorities, for example), some have no formal authority and exist purely at the request of other organizations, while jurisdictions such as cities and counties enjoy recognition in and derive authority from a state constitution. This often creates legal, hierarchical relationships among the decentralized
owners and operators of a region’s transportation system, raising such questions as *who has authority to operate certain pieces of the network?* and *does entity X have the authority to intervene with or overrule the operations of entity Y?*. Regional ITS Architectures do not fully explore these questions in setting out a vision for regional integration. Our work using DSMs to represent relationships, on the other hand, is flexible enough to accommodate, perhaps even identify, such hierarchical structures within an institutional setting. Such accommodation may not alter the results of clustering to a large extent, but could prove useful and instructive in the DSM representation. Consider that communications in our team-based DSMs flow from column elements to row elements. If a DSM were constructed to represent flow of control rather than communication, the resulting asymmetrical matrix could be analyzed with clustering or simply compared with other clustering results to point out hierarchical relationships that complicate or complement clustered structures.

Finally, as previously indicated, some researchers have promoted the notion of establishing new organizations to act as regional integrators, while many others look to such efforts as Regional ITS Architectures to define technological solutions that link agencies without requiring a new region-wide organization for operations akin to the MPO for planning. What emerge from DSM analysis, however, are sub-structures within the region that neither require the creation of new region-wide organizations nor benefit necessarily from maintenance of the status quo for the scale of existing organizations’ operations. In fact, in between the large, regional scale and the small, independent-agency or jurisdiction scale exist modestly-scaled clusters. The question for regional leaders, as posed and discussed above, is whether to interpret the existence of clusters as a need for spawning new agencies to span a cluster and serve as a common focal point, whether to allow agencies to link themselves informally into clusters, or whether to consider consolidating agencies that clustering suggests may fare particularly well if operated as a single entity. Political scientists have explored institutional phenomena such as informal coordination in multi-organizational environments. Donald Chisholm, for example, explored the informal and formal aspects of relationships among transit agencies in the San Francisco Bay Area. He ultimately suggests that establishing a hierarchy or centralization of transit agencies is not necessary due to the proliferation of
informal interactions among them already. Clusters may serve as ideal tools for application in such environments, where centralization is not a viable option yet some communications efficiency gains and operational improvements can be realized.

6.5 Chapter Summary

In this chapter, we have presented several techniques for analyzing, evaluating, and applying DSM clustering results. Sensitivity analysis should include several dimensions: several runs of the same DSM in order to find a "lowest-cost" solution; variation of parameters such as powec in order to observe different possible clustering configurations; and variation of the weighing scheme, if one is used, in order to ensure that potentially efficient or effective arrangements are not overlooked by the algorithm due to a poor choice in weighing scheme. The Yu algorithm simplifies sensitivity analysis because a clustering result is more likely to be globally-optimal (based on minimum description length) than a Fernández/Thebeau clustering result (based on arbitrarily-defined coordination cost). In addition, we propose several methods for evaluating clustering results, including measuring their efficiency and feasibility. Effectiveness is more difficult to measure directly from the DSM, although one can assume in cases such as DSM #5 that the matrix entries represent "benefits" or effectiveness of a linkage rather than costs, and clustering then maximizes effectiveness by identifying dense, multi-lateral, effectiveness-based communication interfaces. An evaluation technique for measuring the trade-off between efficiency and effectiveness involves mismatch analysis, whereby effectiveness-based and efficiency-based DSMs are compared.

The chapter also discusses potential applications of clustering results, which range from identification of informal institutional linkages for facilitated deployment of technology to outright consolidation of organizations. In between, leaders may choose to utilize clusters for construction of physical communications linkages, scenario planning, scheduling of network activities, and a variety of other schemes. Usage of clustering is hindered by several complications, however, including constraints imposed by hierarchical relationships; resistance to formation of new organizations, ceding of authority to existing organizations, or sharing control among existing organizations; and temporal and mission mismatches.
Chapter 7

Conclusions

This thesis has explored several issues in urban transportation, including scale of transportation operations and configuration of institutions, particularly as they deploy technology on their infrastructure. This chapter briefly summarizes the findings of this thesis with respect to the hypotheses we advanced in Chapter 1. We also present some paths for future research that can explore issues related to this work.

7.1 Summary of hypotheses and findings

We began with a review of literature from the following, perhaps seemingly disparate, fields: self-organizing systems, optimal sizing of complex systems, decentralization versus centralization in several fields including various transportation modes and Intelligent Transportation Systems (ITS), Regional ITS Architectures, Regional Strategic Transportation Planning (RSTP), and Design Structure Matrices (DSMs). Armed with the insights of these fields, we hypothesized the following:

- Design structure matrices (DSMs) are helpful analysis tools for representing complex, decentralized systems straightforwardly. Describing urban transportation organization relationships as DSMs is an improvement over existing description methods such as Regional ITS Architectures.
- Clustering algorithms for DSMs offer an opportunity to arrange a region’s organizations more efficiently than the ad-hoc methods currently pursued by
ITS architectures that identify only pair-wise relationships; furthermore clustering identifies potential multi-lateral relationships among organizations that are not recognized by regional architectures.

- Alternative, potentially more effective bases for integration strategies and identification of inter-organization connections than stakeholder-based analyses exist, including those based on physical connectivity and travel demand.

- DSM and DSM clustering satisfy more strongly and unambiguously the United States Federal Highway Administration (FHWA) requirement that ITS architectures and deployment strategies follow a systems engineering approach.

Following a discussion of decentralization, in which a typology of decentralization dimensions was presented, we proceeded to describe the DSM representation and clustering analysis techniques for examining the institutional architecture of urban transportation systems, using the Seattle and Puget Sound region as a case for evaluation. Given our DSM clustering results and evaluation of those results, we present the following findings:

- Transportation organizations in urban regions—cities, counties, state DOTs, transit agencies, port authorities, emergency responders, and others—constitute a decentralized set of entities. Their operations and activities require integration (via creation of new organizations, consolidation of existing organizations, or establishment of linkages among existing organizations) in order to produce more effective system management, which ultimately, in principle, translates into seamless transportation services to users.

- DSMs offer comprehensive methods for detailed representation of decentralized urban transportation organizations and their interactions.

- The appropriate scale of operations for any individual organization depends on its mission, the preferences and characteristics of its managers, and the characteristics of its region. Nonetheless, DSM clustering is a useful technique
for identifying potentially appropriate groupings, also called teams or clusters, of organizations. Once subject to sensitivity analysis and examined within the context of potentially complicating issues as described in Chapter 6, cluster members can be considered for any of a variety of integration efforts, ranging from the establishment of informal, multi-lateral relationships to outright consolidation. Another potential application for cluster members is to identify teams for scenario planning.

- The current basis for designating connections among decentralized urban transportation organizations (mutual, pair-wise stakeholder agreement as embodied by Regional ITS Architectures) suffers several drawbacks. A potentially constructive alternative to this method is physical-connectivity- or travel-demand-based designation of linkages. This alternative is also amenable to DSM representation and clustering analysis.

- Although DSM representation and clustering analysis stand to benefit from additional refinement, the techniques offer the potential to improve regional architectures and organizational integration. If explicitly used as part of Regional ITS Architectures and architecture integration strategies, they more unambiguously satisfy federal regulations requiring that architectures and integration strategies follow a "systems engineering" approach.

7.2 Future work

This section discusses several avenues for further advancement of the study of transportation institutional issues, DSMs, and clustering. In particular, we discuss two directions for further study: DSM representation and clustering algorithms.

In this thesis, we analyzed 5 DSMs with elements such as cities, counties, state DOTs, and transit agencies. Using these organizations as elements was convenient because they correspond with the lists of organizations identified in Regional ITS Architectures and their geographic jurisdictions were clearly defined. A more comprehensive DSM representation could include elements at a more detailed level, such as specific, functional city departments, state DOT divisions, or transit agency departments. By decomposing the organizations into more elemental pieces, we can
represent flows at a more detailed level and identify relationships and clusters within and across organizations rather than just across them. Inclusion of private sector stakeholders would also provide a more complete organizational representation. In addition, future research, particularly for more detailed DSMs, should include extend sensitivity analyses of DSMs to the two dimensions not covered in this thesis: first, varying the weighing scheme used and secondly, varying the organizations included in the DSM.

Sgouris Sgouridis (2005) discusses the challenges and benefits of integrating the public-sector transportation planning process and the private-sector supply chain management (SCM) process.\textsuperscript{49} He considered DSM representation and clustering as one of several approaches for analyzing and evaluating the SCM process. His work provides background and considerations which might guide inclusion of the private sector in DSM representation and regional architecture development. More comprehensive and detailed DSM analyses might suggest more drastic restructuring of organizations both internally and externally than the restructuring identified and suggested in this thesis, while inclusion of SCM processes may identify opportunities for privatization of certain activities.

Bernardo Ortiz (2005) also described an institutional architecture for planning and operations in an unusually complex institutional environment, Mexico City, whose highly decentralized stakeholder organizations far outnumber the organizations in typical American metropolitan areas.\textsuperscript{50} The framework suggested by Ortiz could serve as an alternative basis for Regional ITS Architectures to the DSM-based architectures proposed here. Alternatively, DSMs could support the formulation of a specific architecture that uses the Ortiz framework.

The clustering algorithm itself merits further refinement. Manual clustering of the DSMs that we considered is a nearly impossible task. The Fernández/Thebeau algorithm provides a useful approach for discovering efficient and effective clusters, but does not guarantee an optimal solution. As we found, in fact, the algorithm can find as many as a dozen, perhaps more, distinct results for a given DSM. Yu, et al. developed a rigorous genetic algorithm that is more likely to achieve a globally-optimal solution according to a model description-length metric rather than coordination cost. The Yu algorithm also carries two unfortunate disadvantages: it is patented by the University of Illinois at
Urbana-Champaign which reduces its accessibility, and it requires much more computation power and time than the Fernández/Thebeau algorithm. Fernández/Thebeau may prove useful in many regional contexts so long as analysts recognize its shortcomings. Meanwhile, an algorithm that can improve the consistency of clustering results will be an interesting and valuable task for DSM researchers to undertake.

Lastly, determining methods for measuring the effectiveness of various clustering results is needed. Although efficiency gains are certainly desirable, to claim that more efficient institutional structures with greater ease of communications deliver more effective transportation services is a somewhat ambiguous assertion. By demonstrating the connection between efficient communications and more effective operations of a transportation system, we can conclude more convincingly that DSM and clustering as analysis tools for the transportation system ultimately deliver benefits to the transportation network.

7.3 A closing word

Evaluating organizational architectures can be a daunting research problem due to the political and technical dimensions that complicate analyses and results. Prior attempts to analyze, evaluate, and/or integrate decentralized organizations, whether in practice or in research, are often characterized by ad-hoc approaches. This thesis presents systematic analysis techniques in DSM representation and clustering that, although they will benefit from further refinement, offer promise for improving the pace and efficiency of technology deployment and ultimately improving transportation system performance.

We hope that other researchers will see this as an opportunity to advance analysis and evaluation of institutional issues in the transportation field.
Appendix A

FHWA Final Rules on Regional ITS Architectures and project implementation

The following text is from: United States DOT. Federal Highway Administration. ITS Architecture Implementation Program. Final Rule on Intelligent Transportation System Architecture and Standards.

Section 940.9: Regional ITS Architecture

a. A regional ITS architecture shall be developed to guide the development of ITS projects and programs and be consistent with ITS strategies and projects contained in applicable transportation plans. The National ITS Architecture shall be used as a resource in the development of the regional ITS architecture. The regional ITS architecture shall be on a scale commensurate with the scope of ITS investment in the region. Provision should be made to include participation from the following agencies, as appropriate, in the development of the regional ITS architecture: highway agencies; public safety agencies (e.g., police, fire, emergency/medical); transit operators; Federal lands agencies; State motor carrier agencies; and other operating agencies necessary to fully address regional ITS integration.

b. Any region that is currently implementing ITS projects shall have a regional ITS architecture by [Insert date 30 days after publication in the Federal Register plus 48 months].

c. All other regions not currently implementing ITS projects shall have a regional ITS architecture within four years of the first ITS project for that region advancing to final design.

d. The regional ITS architecture shall include, at a minimum, the following:

1. A description of the region;
2. Identification of participating agencies and other stakeholders;
3. An operational concept that identifies the roles and responsibilities of participating agencies and stakeholders in the operation and implementation of the systems included in the regional ITS architecture;

4. Any agreements (existing or new) required for operations, including at a minimum those affecting ITS project interoperability, utilization of ITS related standards, and the operation of the projects identified in the regional ITS architecture;

5. System functional requirements;

6. Interface requirements and information exchanges with planned and existing systems and subsystems (for example, subsystems and architecture flows as defined in the National ITS Architecture);

7. Identification of ITS standards supporting regional and national interoperability; and

8. The sequence of projects required for implementation.

e. Existing regional ITS architectures that meet all of the requirements of paragraph (d) of this section shall be considered to satisfy the requirements of paragraph (a) of this section.

f. The agencies and other stakeholders participating in the development of the regional ITS architecture shall develop and implement procedures and responsibilities for maintaining it, as needs evolve within the region.

Section 940.11: Project Implementation

a. All ITS projects funded with highway trust funds shall be based on a systems engineering analysis.

b. The analysis should be on a scale commensurate with the project scope.

c. The systems engineering analysis shall include, at a minimum:

1. Identification of portions of the regional ITS architecture being implemented (or if a regional ITS architecture does not exist, the applicable portions of the National ITS Architecture);

2. Identification of participating agencies roles and responsibilities;

3. Requirements definitions;

4. Analysis of alternative system configurations and technology options to meet requirements;

5. Procurement options;
6. Identification of applicable ITS standards and testing procedures; and

7. Procedures and resources necessary for operations and management of the system.

d. Upon completion of the regional ITS architecture required in §§ 940.9(b) or 940.9(c), the final design of all ITS projects funded with highway trust funds shall accommodate the interface requirements and information exchanges as specified in the regional ITS architecture. If the final design of the ITS project is inconsistent with the regional ITS architecture, then the regional ITS architecture shall be updated as provided in the process defined in § 940.9(f) to reflect the changes.

e. Prior to the completion of the regional ITS architecture, any major ITS project funded with highway trust funds that advances to final design shall have a project level ITS architecture that is coordinated with the development of the regional ITS architecture. The final design of the major ITS project shall accommodate the interface requirements and information exchanges as specified in this project level ITS architecture. If the project final design is inconsistent with the project level ITS architecture, then the project level ITS architecture shall be updated to reflect the changes. The project level ITS architecture is based on the results of the systems engineering analysis, and includes the following:

1. A description of the scope of the ITS project;

2. An operational concept that identifies the roles and responsibilities of participating agencies and stakeholders in the operation and implementation of the ITS project;

3. Functional requirements of the ITS project;

4. Interface requirements and information exchanges between the ITS project and other planned and existing systems and subsystems; and

5. Identification of applicable ITS standards.

f. All ITS projects funded with highway trust funds shall use applicable ITS standards and interoperability tests that have been officially adopted through rulemaking by the DOT.

g. Any ITS project that has advanced to final design by [Insert the effective date of this rule] is exempt from the requirements of paragraphs (d) through (f) of this section.
Appendix B

Seattle cluster membership

Table A-1: Cluster membership for DSM #3

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<th>DSM #</th>
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<th>Members</th>
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<td>2</td>
<td>Tacoma, Tacoma Narrows Bridge, WSDOT Olympic</td>
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<tr>
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<td>3</td>
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<tr>
<td></td>
<td>5</td>
<td>Lakewood, University Place</td>
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<tr>
<td></td>
<td>6</td>
<td>Renton, Tukwila</td>
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<tr>
<td></td>
<td>7</td>
<td>Seattle, Shoreline</td>
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<td>Edgewood, Pierce County</td>
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<tr>
<td></td>
<td>10</td>
<td>Auburn, Kent</td>
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Table A-2: Cluster membership for DSM #4

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<td>Bellevue, Issaquah, Seattle, Shoreline</td>
</tr>
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<td></td>
<td>5</td>
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<td>-----------</td>
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|       | 1         | Edmonds  
|       |           | Lynnwood  
|       |           | Mountlake Terrace  
|       |           | Community Transit  
|       |           | Everett Transit  
|       |           | Kitsap Transit  
|       |           | Sound Transit (LINK)  
|       |           | Sound Transit (Regional Express)  
|       | 2         | Arlington  
|       |           | Bothell  
|       |           | Everett Transit  
|       |           | Marysville  
|       |           | Mill Creek  
|       |           | Snohomish  
|       |           | Stanwood  
|       | 3         | Seattle  
|       |           | Shoreline  
|       |           | Other Seattle Venue  
|       |           | Parking Operator  
|       |           | Seattle Center  
|       | 4         | SeaTac Airport  
|       |           | Amtrak  
|       |           | ITS Data Backbone  
|       |           | Smart Trek  
|       | 5         | Sound Transit (Sounder)  
|       |           | Sumner  
|       |           | Puyallup  
|       | 6         | Washington State Ferries  
|       |           | Bainbridge Ferry Terminal  
|       |           | Kingston Ferry Terminal  
|       | 7         | Pierce Transit  
|       |           | Puyallup  
|       |           | Gig Harbor  
|       | 8         | Federal Way  
|       |           | SeaTac Airport  
|       |           | King County Metro  
|       | 9         | Tacoma  
|       |           | Tacoma Narrows Bridge  
|       |           | WSDOT Olympic  
|       | 10        | Kent  
|       |           | Renton  
|       |           | Tukwila  
|       | 11        | Bremerton  
|       |           | Kitsap County  
|       |           | Silverdale  

1: All Market Packages, Binary
Table A-4: Cluster membership for DSM #2

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|       |           | Amtrak  
|       |           | ITS Data Backbone  
|       |           | Other Seattle Venue  
|       |           | Parking Operator  
|       |           | Seattle Center  
|       |           | Smart Trek  
|       | 2         | Arlington  
|       |           | Bothell  
|       |           | Everett  
|       |           | Marysville  
|       |           | Mill Creek  
|       |           | Snohomish  
|       |           | Stanwood  
|       | 3         | Everett Transit  
|       |           | Sound Transit (LINK)  
|       |           | Sound Transit (Regional Express)  
|       |           | Sound Transit (Sounder)  
|       |           | Sumner  
|       | 2: All Market Packages, Weighted | Edgewood  
|       |           | Lakewood  
|       |           | Pierce County  
|       |           | University Place  
|       | 4         | Edmonds  
|       |           | Lynnwood  
|       |           | Mountlake Terrace  
|       |           | Community Transit  
|       | 5         | Bremerton  
|       |           | Kitsap County  
|       |           | Silverdale  
|       |           | Kitsap Transit  
|       | 6         | Washington State Ferries  
|       |           | Bainbridge Ferry Terminal  
|       |           | Kingston Ferry Terminal  
|       | 7         | Pierce Transit  
|       |           | Puyallup  
|       |           | Gig Harbor  
|       | 8         | Federal Way  
|       |           | SeaTac  
|       |           | King County Metro  
|       | 9         | Tacoma  
|       |           | Tacoma Narrows Bridge  
|       |           | WSDOT Olympic  
|       | 10        | Kent  
|       |           | Renton  
|       |           | Tukwilla  
|       | 11        |  

122
### Table A-5: Cluster membership for DSM #5

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<tr>
<td></td>
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Appendix C

Complete list of Seattle organizations

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<th>MARKET PACKAGE PARTICIPANTS</th>
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<td>City of Mountlake Terrace</td>
<td>Woodway</td>
</tr>
<tr>
<td>City of Edmonds</td>
<td>Woodway</td>
</tr>
<tr>
<td>City of Everett</td>
<td>Yarrow Point</td>
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EMERGENCY MANAGEMENT

Ambulance Services
Hospitals
Local Fire
Local Police

OTHER EMERGENCY RESPONSE

Washington State Patrol
WSDOT Incident Response

INFORMATION SERVICE PROVIDERS (ISPs)

Agency-Operated ISPs
Private ISPs
City of Shoreline
City of Kent
City of Bremerton
City of Tacoma
City of Puyallup
City of Lakewood
City of Gig Harbor
City of University Place
Pierce County
City of Sumner

**TRANSIT FARE MANAGEMENT**
- Community Transit
- Everett Transit
- King County Metro
- Kitsap Transit
- Pierce Transit
- Sound Transit (LINK)
- Sound Transit (Regional Express)
- Sound Transit (Sounder)
- Washington State Ferries

**TRANSIT TRAVELER INFORMATION**
- Community Transit
- Everett Transit
- King County Metro
- Pierce Transit
- Sound Transit (LINK)
- Sound Transit (Regional Express)
- Washington State Ferries
- Bainbridge Ferry Terminal
- Kingston Ferry Terminal
- Sound Transit (Sounder)

**COMMERCIAL VEHICLE ADMINISTRATION**
- Fleet and Freight Management
- Burlington Northern Santa Fe
- Union Pacific
- Shipping Companies
- Trucking Companies
- Department of Licensing

**WASHINGTON STATE PATROL**
- WSDOT
- Washington Trucking Association
- Ports
- US Customs

**TRANSIT MANAGEMENT**
- Community Transit
- Everett Transit
- Kitsap Transit
- King County Metro
- Pierce Transit
- Sound Transit
- Washington State Ferries

**FEDERAL LANDS**
- Mt. Rainier National Parks
- Mount Baker/Snoqualmie
- National Forest
Appendix D

References

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Chapter 7
