USING DESIGN STRUCTURE MATRICES TO IMPROVE DECENTRALIZED URBAN TRANSPORTATION SYSTEMS

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INTRODUCTION

The provision of urban transportation infrastructure and services occurs in a decentralized institutional setting. Facility owners include, among others, municipalities, state governments, the national government, port authorities, private companies, and railroads. Service providers often include numerous private and public mass transit agencies, taxi services, and others. Several impending transformations in the transportation field suggest that the effectiveness of such a decentralized structure may be limited; integration of activities and formalization of relationships, therefore, may become desirable. The availability of advanced information technology, for example, enables and sometimes requires multiple organizations to share data, control, and authority with greater frequency than they have traditionally. In addition, the emergence of a regional perspective for planning necessitates the involvement of more stakeholders than ever before in metropolitan transportation planning, project development, and operations. Congestion, coupled with the decreasing availability of resources for conventional infrastructure, has produced a need for innovative technological, operational, and managerial solutions that span the jurisdictions of many organizations.

In anticipation of these transformations, transportation researchers and decision-makers in recent years have recognized the importance of specifying relationships among organizations in a region. Regional Intelligent Transportation System (ITS) Architectures, specifically, have been developed for many American metropolitan areas and states. These architecture documents prescribe both the technical and institutional linkages between organizations to facilitate the deployment, operations, and maintenance of advanced technologies for transportation infrastructure. In many cases, however, the provision of organizational linkages is constrained by the architecture development process, which calls for inclusion of and agreement among as many stakeholders as possible. The resulting institutional architectures often consist of pairwise linkages between organizations. A broader view of the urban transportation institutional setting, however, can reveal multilateral linkages that afford the opportunity for more efficient deployment and operations of ITS and more effective transportation services.

This paper introduces the design structure matrix (DSM) and the clustering technique, developed in the fields of industrial and systems engineering, as tools for transportation technology planning. The DSM offers a convenient platform for representing all elements of a complex system, and clustering algorithms can suggest more efficient organizational structures. In this paper, we apply DSMs and clustering to the organizational structures specified by a Regional ITS Architecture for the Puget Sound region (Seattle, WA) in order to identify potentially more efficient institutional architectures that can ultimately lead to more effective transportation operations, providing better service to customers.

BACKGROUND

Decentralized Systems

From where does authority emanate in a complex organizational environment? At one extreme, authority can be distributed horizontally among a set of autonomous actors whose actions and interactions produce a functional, coordinated system. Such self-organization is apparent in natural and sociological phenomena such as ant colonies, bird flocks, and traffic jams (1). At the other extreme, authority emanates from a central controller. The debate between centralized and decentralized control of a system exists in a number of fields, from philosophy,
economics, and political science to product design and systems engineering (2; 3, 4, 5, and 6; 7 8, and 9).

In transportation, this issue of centralization versus decentralization recurs in a variety of modes, including railroads, aviation, and highways. The Union Pacific Railroad, for example, opened a centralized command center in 1989, from which employees managed all dispatching on the rail network, crew scheduling, maintenance scheduling, and other operating functions (10). Following a merger with the Southern Pacific railroad in 1997, however, UP experienced an unprecedented service crisis. Observers and participants attributed many operating difficulties to the shock of centrally managing an extensive new post-merger network (11). UP responded in part by restructuring its operations toward a more decentralized configuration, putting greater emphasis on the power of local managers to make some operational decisions (12). As with railroads, air traffic management derives benefits from both centralized and decentralized system elements. American airspace is managed by the Federal Aviation Administration, but communications and daily operations are delegated to geographic sub-regions, most notably the 20 Air Route Traffic Control Centers (ARTCC’s, or Centers) throughout the lower 48 states. The geographically-decentralized elements “enable local flexibility and a tailoring of services to meet the needs of users at the local level” (13). Meanwhile, a centralized feature, the ATC System Command Center located in Herndon, VA, monitors air traffic conditions and incidents system-wide, although with less detail. In the highway realm, researchers working on dynamic traffic guidance have taken several approaches to the problem of providing real-time guidance that is both meaningful and accurate. Although most agree that a centralized view of a regional road network is required in order to produce useful, effective guidance, several computational techniques involve geographic decentralization (e.g., 14, 15, and 16). In the latter cases, guidance is computed by several local controllers based on local information rather than by a single, centralized controller. The advantage of decentralized control is to compute guidance more quickly at the expense of a guidance solution that is optimal region-wide.

Although some hierarchical relationships exist among urban transportation organizations, the institutional structure governing them is largely decentralized. In a complex environment such as urban transportation, both a centralized decision-maker model and a fully decentralized organizational model will experience difficulties with such tasks as deploying technology or operating a roadway network.

The goal of this paper is to improve upon the institutional architectures for urban regions by introducing a technique capable of identifying teams or “clusters” of organizations at the sub-regional level based on pre-existing levels of interaction. A cluster, without constituting a regionally-centralized organization, can reduce the complexity of interactions within a decentralized web of organizations. Next, we describe the clustering technique, which later we apply to organizations involved in technology deployment in the Seattle area.

**Design Structure Matrices**

Steward (17) introduced the design structure matrix (DSM) as an analysis tool for complex systems. In the ensuing two decades, researchers in mechanical engineering, systems engineering, and management have modified and expanded DSM manipulation techniques and applications. Among the advantages of using these techniques, researchers and managers can more easily identify opportunities to improve the efficiency of interactions between organizations.
There are four DSM categories; the authors feel transportation organizations and their linkages are best represented as team-based DSMs, which 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. Figure 1 contains a simple, illustrative 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. They do not, however, communicate with cleaning staff, hosts, or owners.

A few items of particular interest stand out in Figure 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 DSM literature, such entities are often regarded as integrating teams, system-wide integrators, or simply buses. Next, the main diagonal 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 pairwise relationships with no exchange of information are left blank. Typically, for purposes of computation, DSMs represent each “x” and diagonal cell as a 1 and each blank cell as a 0, resulting in a binary numerical representation of flows in the matrix.

**Figure 1: Example team-based DSM of a restaurant**

Numerical representation can be extended to include weighted entries that reflect the importance of a relationship or the degree of information exchange. In Figure 1, for example, wait staff and cooks exchange large volumes of information intensely and almost continuously.
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 (or probability of communication over a given time period) 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.

**Clustering**

Team-based DSMs are manipulated using clustering algorithms. Clustering 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. By recognizing the set of relationships among teams, the teams can more readily anticipate and participate in information exchange and communication.

The underlying assumption of clustering is 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 (e.g., 18, 19, 20). 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 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, as shown conceptually on the right side of Figure 2, whether a physical connection or some form of contractual relationship. In other words, clustering identifies multilateral relationships among organizations that promise to deliver greater efficiency than pairwise connections.
Figure 2: Conceptual illustration of the efficiency benefit of identifying clusters

The most basic clustering algorithms involve manual manipulation of a matrix (e.g., 18). In Figure 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. 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 3: Manually-clustered restaurant DSM
More advanced, automated clustering algorithms attempt to optimize the arrangement of the matrix elements into clusters by searching for lower-cost solutions to the problem of information exchange, again assuming that intra-cluster communications are less costly than extra-cluster communications. Fernández (19), 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. 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, through a process called simulated annealing. Thebeau (20) 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.

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:

\[
\text{Intracluster Cost} = [\text{DSM}(j,k) + \text{DSM}(k,j)] \cdot \text{ClusterSize}(y)^{\text{powcc}} \quad (1)
\]

\[
\text{Extraccluster Cost} = [\text{DSM}(j,k) + \text{DSM}(k,j)] \cdot \text{DSMSize}^{\text{powcc}} \quad (2)
\]

\[
\text{Total Cost} = \sum \text{Intracluster Cost} + \sum \text{Extraccluster Cost} \quad (3)
\]

In the above equations, the cost of an intra-cluster relationship is determined by multiplying a matrix entry by the size of its cluster and raising the product to a power \( \text{powcc} \). Extra-cluster costs are modeled as a multiple of the dimension of the DSM raised to the same power, \( \text{powcc} \). Since clusters are smaller than the entire DSM (except for the case of one universal cluster), the extra-cluster cost is larger than the intra-cluster cost for any relationship. Small, nonnegative values of \( \text{powcc} \) tend to create matrices with higher numbers of relatively small clusters since the penalty to intra- and extra-cluster relationships is similar. At some larger value of \( \text{powcc} \), depending on the size and composition of a particular DSM, larger clusters emerge as more common, since the penalty is larger for extra-cluster relationships.

**REGIONAL ITS ARCHITECTURES AS APPLICATIONS FOR DSM REPRESENTATION AND CLUSTERING**

A Regional ITS Architecture generally includes a description of a metropolitan region, its transportation systems, and stakeholders involved in ITS deployment and systems management. *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, flow charts, and textual descriptions. Furthermore, the document typically specifies “market packages” of ITS technologies relevant to the region. Many of these packages require little or no organization-to-organization interaction; others, however, require significant interactions. We identify the latter packages and their interactions as having the greatest opportunity for eliminating inefficiencies through DSM representation and clustering analysis.

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” (21). Examples of market packages include transit vehicle tracking, transit passenger and fare management, interactive traveler information, electronic toll collection, regional traffic control, railroad operations coordination, international border electronic clearance, emergency response, and incident management. The National Architecture leaves the task of identifying relevant market packages in specific regions to the regions themselves. Once identified, regions also must determine at what geographic scale to apply the market packages. In the Seattle region, for example, “most market packages do not require interaction with other organizations, and can be generally implemented as stand-alone applications locally” (21). 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. Authors of the Seattle architecture identified 9 market packages requiring cross-jurisdictional interaction. One of these packages—the “regional traffic control” package—is of interest for this paper.

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 all the agencies required for deployment of each market package, a list of other institutions with which they 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 (21). These interactions are defined on a pairwise basis; that is, they specify connections between only two organizations at a time.

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 the 45 organizations participating in the regional traffic control market package. 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 defined above as prescribed by the architecture. Third, we will construct a DSM using 63 organizations in the Seattle area, but indicate a relationship between any two only if they are physically adjacent or overlapping. In this case, we assume that organizations with jurisdictions in close proximity will require interaction, whereas those separated by other jurisdictions will not. In all cases, DSMs will be clustered according to the cost-based optimization algorithm developed by Fernández and Thebeau.

RESULTS

Each figure in this section presents a “before clustering” and an “after clustering” DSM. Before clustering, the elements (Seattle-area transportation organizations) are ordered alphabetically; after clustering, they are ordered according to the arrangement suggested by the clustering algorithm. In all three cases, the powcc parameter is assigned a value of 1.

The stability of the results is a function of the input parameters such as the number of elements in the matrix, the number of non-zero entries in the matrix, the value of the parameter powcc, and the value of parameters that determine the number of iterations before the algorithm stops searching for new solutions. The clustering algorithm is path dependent, however, and the
“path” is determined by random selection of elements. This means that the algorithm often finds several distinct solutions even when all parameters are held constant. By using the total coordination cost as a measure, we selected the lowest-cost solution out of twenty-five possible arrangements in each of the three cases.

The three DSMs are shown in Figures 4, 5, and 6. Figure 4 shows the clustering results for a binary DSM of 45 organizations participating in the regional traffic control market package; Figure 5 shows clustering results for the same 45 organizations but with weighted entries instead of binary; Figure 6 shows clustering results for a group of 63 organizations based on their physical proximity. Arrows along the upper edge of the clustered DSMs indicate “buses” that were identified prior to clustering, removed from the DSM, and then reinserted after clustering. In the first two cases, the buses correspond to King County and the Northwest District of the Washington State DOT (WSDOT); in the third case, the buses correspond to WSDOT Northwest, King County, and 3 transit agencies that serve multiple counties in the region.
Figure 4: Binary DSM of Seattle traffic-control organizations; clustering based on Regional ITS Architecture

Figure 5: Weighted DSM of Seattle traffic-control organizations; clustering based on Regional ITS Architecture
Table 1 summarizes the coordination cost metric in each of the above three cases, indicating the starting cost, ending cost, and percentage improvement. The coordination costs of the three DSMs are not comparable because their sizes and cell contents vary significantly, which puts the computation in each case on different footings. The purpose of the table is to illustrate the benefits to each DSM independently. Ranking the clustering results or selecting a preferred clustered DSM should not rely on the coordination cost improvements alone, but also consider the number and size of clusters and their memberships.

**TABLE 1: Before and after coordination costs for the 3 DSMs**

<table>
<thead>
<tr>
<th>DSM</th>
<th>Description</th>
<th>Starting cost</th>
<th>Ending cost</th>
<th>Cost improvement</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>Binary, traffic control</td>
<td>3110</td>
<td>1540</td>
<td>50%</td>
</tr>
<tr>
<td>2</td>
<td>Weighted, traffic control</td>
<td>504</td>
<td>129</td>
<td>74%</td>
</tr>
<tr>
<td>3</td>
<td>Binary, physical proximity</td>
<td>1410</td>
<td>854</td>
<td>40%</td>
</tr>
</tbody>
</table>

**DISCUSSION**

In this section, we discuss the usefulness of clustering results according to three evaluation metrics. We also explain the meaning of the results for transportation organizations in general and for Seattle transportation organizations in particular. Metrics to determine the viability of the clustered DSMs include *efficiency, effectiveness, and feasibility*.

The “total coordination cost” measure is substantially reduced in each case, indicating that the clustered arrangements all promise better *efficiency* than the unclustered arrangements. Organizations can derive these efficiency gains from multilateral deployment efforts in the short term and from multilateral interactions in longer-term operations. This does not necessarily mean, however, that the new arrangement will also be more *effective*, in terms of improved...
traffic conditions. We can hypothesize that more efficient interactions afford these sorts of effectiveness improvements, but they cannot be measured simply by considering the clustered DSM.

**Feasibility** measures the willingness of stakeholders to agree to the new, clustered institutional arrangement. The unclustered DSMs are representations of pairwise linkages specified in the already-agreed-upon Regional ITS Architecture, which suggests the institutional arrangement has a high degree of feasibility. Although the clustered DSMs do not disturb the existing set of relationships, they do nonetheless suggest new, multilateral relationships which could prove less feasible—that is, more difficult to implement.

**General Implications of Clustering**

There are two categories in which a region may wish to apply clustering results. First, they can be applied simply as a catalyst for more efficient deployment of technology such as ITS. Alternatively, DSM clustering can be used to identify alternative architectures that improve the efficiency of real-time transportation operations long after deployment. In either case, the sub-regional geographic scale of clusters avoids the often undesirable, fully-centralized approach while capitalizing on synergies among existing organizations and simplifying their interactions.

In the short term, 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.

DSM clustering can also identify longer-term architecture improvements. Since individual entities often exist because of historical chance, a cluster can adjust for the inefficiencies and potential operational ineffectiveness of coincident structures by pointing toward a new structure that combines several previously un-integrated entities. Most simply, a cluster merely suggests a set of organizations to which all the members should devote resources to build informal, multilateral relationships. More dramatically, a cluster may suggest outright consolidation of its several members. Between these two extremes, 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 themselves.
- 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 multilateral 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, sporting events, crises such as a terrorist attack, or response to extreme weather conditions such as a blizzard or hurricane.
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, 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.

Implications of Clustering for the Seattle Region

For further illustration, Figure 7 demonstrates a clustering result for Seattle after increasing the value of the parameter powcc to 100. Table 2 provides a list of the members of each of the four largest clusters outlined in Figure 7 (unless otherwise specified, the organizations are towns and cities). As one might expect, cluster members tend to be located relatively near one another. For example, cluster #2 consists of the towns of Edgewood, Lakewood, Tacoma, and University Place; Pierce County; Olympic District of WSDOT; and the Tacoma Narrows Bridge. Having highlighted this group through clustering, a regional architecture could then suggest that the members devote staff and resources to a common pool among the seven organizations, rather than developing institutional relationships in an ad-hoc, pairwise fashion between more than a dozen pairs of organizations.
The level of commitment and authority of this “common pool” can range as described in the bulleted list of options. Perhaps the member agencies are particularly synergistic and wish to merge their activities, or a portion of their activities, into a single organization; perhaps they wish to maintain an informal communication channel that includes all members rather numerous channels among pairs of members; or perhaps they simply wish to establish situational protocols through scenario planning.

Whatever approaches a region ultimately decides to pursue, even if leaders determine that there is insufficient benefit from clustering altogether, the DSM 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 transportation crises.

**FUTURE WORK**

This research analyzed DSMs with elements such as cities, counties, state DOTs, and transit agencies. Using these organizations as elements in a DSM is convenient because they correspond with organizations identified in Regional ITS Architectures and have clearly-defined
geographic jurisdictions. A more comprehensive DSM representation, however, could include elements at a more detailed level, such as specific, functional city departments, state DOT divisions, or transit agency departments. By decomposing existing organizations into more elemental pieces, we can represent interactions at a more detailed level and identify relationships and clusters within and across organizations rather than just across them. In other words, rather than discovering clustered institutional architectures for existing organizations, DSM representation and clustering can help us to achieve wholesale restructuring and improvements in the efficiency of those organizations and their component functions.

The clustering algorithm itself merits further refinement. Manual clustering DSMs of the sizes that we considered is a nearly impossible task. The Fernández/Thebeau algorithm provides a useful approach for discovering efficient clusters, but does not guarantee an optimal solution. 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.

Lastly, determining methods for measuring the effectiveness of various clustering results is needed. Although efficiency gains are certainly desirable, the claim that more efficient institutional structures with greater ease of communications deliver more effective transportation services needs bolstering. 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 an urban transportation system ultimately deliver benefits to the transportation network and to its customers.

CONCLUSIONS
Transportation organizations in urban regions—cities, counties, state DOTs, transit agencies, port authorities, emergency responders, and others—constitute a decentralized set of entities. The efficiency and future effectiveness of Regional ITS Architectures are limited in part because they largely rely on pairwise linkages between these organizations. DSM clustering is a useful technique for identifying potentially appropriate teams or clusters of organizations that interact multilaterally at a sub-regional level. Cluster members can be considered for any of a variety of integration efforts, ranging from the establishment of informal, multilateral relationships to outright consolidation or for a special-purpose function like scenario planning.

Although DSM representation and clustering will benefit from further refinement, the techniques offer the potential to improve Regional ITS Architectures, specifically, and the efficiency of transportation organizations’ interactions more broadly.
REFERENCES


