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A Quantitative Framework for Assessing Vulnerability and Redundancy of Freight Transportation Networks

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A QUANTITATIVE FRAMEWORK FOR ASSESSING VULNERABILITY AND

REDUNDANCY OF FREIGHT TRANSPORTATION NETWORKS

by

Sarawut Jansuwan

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ABSTRACT

A Quantitative Framework for Assessing Vulnerability and Redundancy of

Freight Transportation Networks

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Sarawut Jansuwan, Doctor of Philosophy

Utah State University, 2013

Major Professor: Dr. Anthony Chen
Department: Civil and Environmental Engineering

This study develops a quantitative framework for assessing vulnerability and redundancy of freight transportation networks. The framework consists of three developments including: (1) development of a method for estimating a statewide truck origin-destination (O-D) trip table, a crucial input for the next two steps, (2) development of a quantitative method and a decision support system tool for assessing vulnerability of freight transportation networks, and (3) development of quantitative measures for evaluating redundancy of freight transportation networks.

The first development is a statewide truck O-D trip table accomplished by a *two-stage approach*. The first stage estimates a *commodity-based* truck O-D trip table using the commodity flows derived from the Freight Analysis Framework (FAF) database, and the second stage uses the *path flow estimator* (PFE) concept to refine the truck O-D trip table. The results from this step provide us a better understanding of truck flows on statewide truck routes and corridors, and allow us to better manage the anticipated

impacts caused by network disruptions. The second development involves building a decision support tool for assessing vulnerability of freight transportation networks. Two network measures, *O-D connectivity* and *freight flow pattern change*, are developed to capture the changes in network connectivity, freight flow patterns, and induced transportation-related costs due to network disruptions. The decision support tool is mainly developed to facilitate decision making using a "*what-if*" analysis approach with different disruption scenarios through the applications of database management capabilities, graphical user interface, GIS-based visualization, and transportation network vulnerability analysis. In the third development, two quantitative measures are developed to characterize the redundancy of freight transportation networks: *route diversity* and *network spare capacity*. The route diversity dimension measures the existence of multiple efficient routes available for freight users, while the network spare capacity dimension quantifies the networkwide spare capacity with an explicit consideration of congestion effect. These two dimensions can complement each other by providing a *two-dimensional* characterization of freight transportation network redundancy. Case studies using the Utah statewide freight transportation networks are conducted to demonstrate the features of the vulnerability and redundancy measures and the applicability of the quantitative assessment methodology. By considering vulnerability and redundancy assessment into the decision making and planning process, agencies would benefit from the proposed framework in supporting their investment decisions, thus creating a more robust and resilient freight transportation network against network disruptions.

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PUBLIC ABSTRACT

A Quantitative Framework for Assessing Vulnerability and Redundancy of

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Freight transportation networks are an important component of everyday life in modern society. Disruption to these networks can make peoples' daily lives extremely difficult as well as seriously cripple economic productivity. This dissertation develops a quantitative framework for assessing vulnerability and redundancy of freight transportation networks. The framework consists of three major contributions: (1) a two-stage approach for estimating a statewide truck origin-destination (O-D) trip table, (2) a decision support tool for assessing vulnerability of freight transportation networks, and (3) a quantitative approach for measuring redundancy of freight transportation networks.

The dissertation first proposes a *two-stage approach* to estimate a statewide truck O-D trip table. The proposed approach is supported by two sequential stages: the first stage estimates a *commodity-based* truck O-D trip table using the commodity flows derived from the Freight Analysis Framework (FAF) database, and the second stage uses the *path flow estimator* (PFE) concept to refine the truck trip table obtained from the first

stage using the truck counts from the statewide truck count program. The model allows great flexibility of incorporating data at different spatial levels for estimating the truck O-D trip table. The results from the second stage provide us a better understanding of truck flows on the statewide truck routes and corridors, and allow us to better manage the anticipated impacts caused by network disruptions.

A decision support tool is developed to facilitate the decision making system through the application of its database management capabilities, graphical user interface, GIS-based visualization, and transportation network vulnerability analysis. The vulnerability assessment focuses on evaluating the statewide truck-freight bottlenecks/chokepoints. This dissertation proposes two quantitative measures: *O-D connectivity* (or detour route) in terms of distance and *freight flow pattern change* in terms of vehicle miles traveled (VMT). The case study adopts a "*what-if*" analysis approach by generating the disruption scenarios of the structurally deficient bridges in Utah due to earthquakes. In addition, the potential impacts of disruptions to multiple bridges in both rural and urban areas are evaluated and compared to the single bridge failure scenarios.

This dissertation also proposes an approach to measure the redundancy of freight transportation networks based on two main dimensions: *route diversity* and *network spare capacity*. The route diversity dimension is used to evaluate the existence of multiple efficient routes available for users or the degree of connections between a specific O-D pair. The network spare capacity dimension is used to quantify the network-wide spare capacity with an explicit consideration of congestion effect. These two dimensions can complement each other by providing a two-dimensional characterization

of freight transportation network redundancy. Case studies of the Utah statewide transportation network and coal multimodal network are conducted to demonstrate the features of the vulnerability and redundancy measures and the applicability of the quantitative assessment methodology.

Sarawut Jansuwan

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<div align="right">Sarawut Jansuwan</div>

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CHAPTER 1

INTRODUCTION AND OBJECTIVES

1.1   General background

Freight transportation network is an essential backbone for supporting the industrial activities and economic developments of the nation and global trade. They are a crucial component of the United State (U.S.) economy, which includes highways, railways, waterways, freight facilities and intermodal terminals. According to the latest figures from the U.S. Federal Highway Administration (U.S. FHWA, 2009), and the U.S. Census Bureau (2010, 2012), the U.S. transportation system transported a total of 17.6 billion tons per year in 2011 to serve almost 117 million households, 7.4 million business establishments. The volume of goods shipped by truck and railroad are projected to increase by 53% and 55% by 2040 from 2007 levels (U.S. FHWA, 2009). The volume of freight transportation will continue to grow over the next decade. The steady growth in freight movements is possible because of growth in the U.S. economy, increases in the U.S. international merchandise trade, improvements in freight sector productivity, and the availability of demand of an extensive multimodal transportation network (Bureau of Transportation Statistics, 2004). Both freight shippers and carriers generally use various modes of transportation: road, rail, water, and air either in individually or in combination to transport goods and raw materials for all stages of the production process in the supply chain.

Although freight transportation networks are critical to functioning of a modern society and industry, they are also fragile. Freight transportation networks are one of the *economic lifelines* which demand meticulous security consideration, especially in the

aftermath of recent disastrous events such as: man-made attacks and natural disasters around the world (e.g., 9/11 terrorist attacks in 2001, Hurricanes Katrina and Rita in 2005, Seattle's Hanukkah Eve Wind Storm in 2006, Minneapolis' Interstate 35 (I-35W) bridge collapse in 2007, Haiti's earthquake in 2010, Japan's tsunami in 2011, Hurricane Sandy in 2012, and so on). These events have not only made life a challenge for locals, but have also impacted freight transportation networks and global supply chains worldwide. Failures of these critical infrastructures (e.g., bridges, tunnels) on freight networks will halt or delay business continuity, industrial production, essential services, and even the national economy. The consequences have emphasized the multi-faceted importance of these networks to society, and the need for government agencies and planner to make freight transportation system more robust and resilient to withstand disaster disruptions.

1.2   The need for this study

Disruption to freight transportation networks can seriously damage the economic productivity of the society as well as making peoples' daily lives extremely difficult (Miller, 2003). Recently, the vulnerability of transportation networks has emerged as an important topic due to the network's critical status as an important *lifeline* (Platt, 1991). Berdica (2002) defined vulnerability as "a susceptibility to incidents that can result in considerable reductions in road network serviceability". "Incidents" are events that can directly or indirectly result in considerable reductions or interruptions in the serviceability of a link/route/road network. Berdica further suggested that vulnerability should include both the probability and consequences of an incident occurring. The reduction of vulnerability is, in such a perspective, similar to the reduction of risk. Once

the vulnerability of physical assets with high criticality such as bridges, tunnels, roadways has been assessed, the countermeasures to deter, detect and delay the consequences can be developed so that the capital and operating costs of such countermeasures can be estimated (AASHTO, 2002). This topic has attracted many researchers to develop various indicators to assess the reliability and vulnerability of transportation networks (see the edited books, proceedings, and special issues by Lam, 1999; Bell and Cassir, 2000; Bell and Iida, 2003; Nicholson and Dantas, 2004; Sumalee and Kurauchi, 2006; Murray and Grubesic, 2007; Kurauchi and Sumalee, 2008; Kurauchi et al., 2009; Schmocker and Lo, 2009; Nagurney and Qiang, 2010; Levinson et al., 2010, 2012; Lam et al., 2012).

Prior research is valuable in setting a basis for assessing transportation network vulnerability. However, the current knowledge for freight transportation is limited due to the lack of empirical insights, models, data, and decision support tools. Current efforts in transportation research tend to focus more on passenger transportation, while the quantitative measures to characterize freight network vulnerability are limited in the literature. The development of quantitative frameworks is particularly important because of the complexity of the problem. The quantitative indices provide necessary basis for comparison of various threats and the trade-off among potential response measures.

Moreover, this study develops quantitative measures to assess the redundancy of freight transportation networks, one of the four "Rs" (i.e., Robustness, Redundancy, Resourcefulness, Rapidity) suggested by Bruneau et al. (2003) for calculating the resiliency triangle. Redundancy is an important indicator in the development of an emergency response and recovery plan (FHWA, 2006). A typical pre-disaster planning

strategy is to improve network resiliency by adding redundancy (e.g., new roadways) to create more alternatives for users or by hardening the existing infrastructures (e.g., retrofitting existing bridges) to withstand disruptions. Although redundancy is a well-known concept, especially for other engineering disciplines (e.g., computer, electrical, water supply system, structural engineering), very few have developed quantitative measures to assess redundancy in transportation as described above, and even less likely to focus on freight transportation networks.

Thus, the primary objective of this research effort is to develop a quantitative framework for assessing vulnerability and redundancy of freight transportation networks, while enhancing the productivity in decision making of the planners and the state DOT with a user-friendly decision support system. The vulnerability and redundancy assessment focuses on evaluating truck-freight bottlenecks/choke points, which are high value according to their potential economic impacts on the U.S. commerce. The current research, hence, starts with the development of a statewide truck origin-destination (O-D) model to capture the truck flow pattern on the statewide truck routes. The truck O-D trip table is an important input for the vulnerability and redundancy assessment process. Growing freight demand has led to the need for better tools to predict the consequence of the transportation network disruptions. A geographic information system (GIS) based visualization tool that combines freight transportation network and statewide truck flows data are developed to enhance the ability in assessing the transportation vulnerability as well as managing the consequences due to disruptions. The tool capabilities are demonstrated using case studies of the disruptions of bridges in the statewide areas. Furthermore, we develop two quantitative measures: *route diversity* and *network spare*

capacity, for assessing freight transportation network redundancy – an important component in making freight transportation networks more robust and resilient against disruptions. These measures are important metrics as they can complement each other by providing a two-dimensional characterization of freight transportation network redundancy.

The metrics, models, tools, and analyses developed in this dissertation are expected to be not only useful to the assessment of vulnerability and redundancy of freight transportation system, but also applicable to other civil infrastructure (e.g., water distribution system). The outcomes of this research are expected to be helpful in assisting the policymakers and planners to understand the vulnerability in transportation networks as well as in making future infrastructure investment decisions to enhance the resiliency of freight transportation networks.

1.3   Research objectives

The objective of this study is to develop a quantitative framework for assessing vulnerability and redundancy of freight transportation network. Specifically, the objectives are to:

Objective 1:   Develop a methodology for estimating a statewide truck origin-destination (O-D) trip table,

Objective 2:   Develop a quantitative approach for assessing potential vulnerability of freight transportation networks,

Objective 3:   Develop a decision support tool that combines database management capabilities, graphical user interface, GIS-based visualization, and transportation network vulnerability analysis,

Objective 4:   Develop a quantitative approach for assessing the redundancy of freight transportation networks.

1.4   Dissertation organization

This dissertation consists of six chapters. The organization of the dissertation is illustrated in Fig. 1.1.
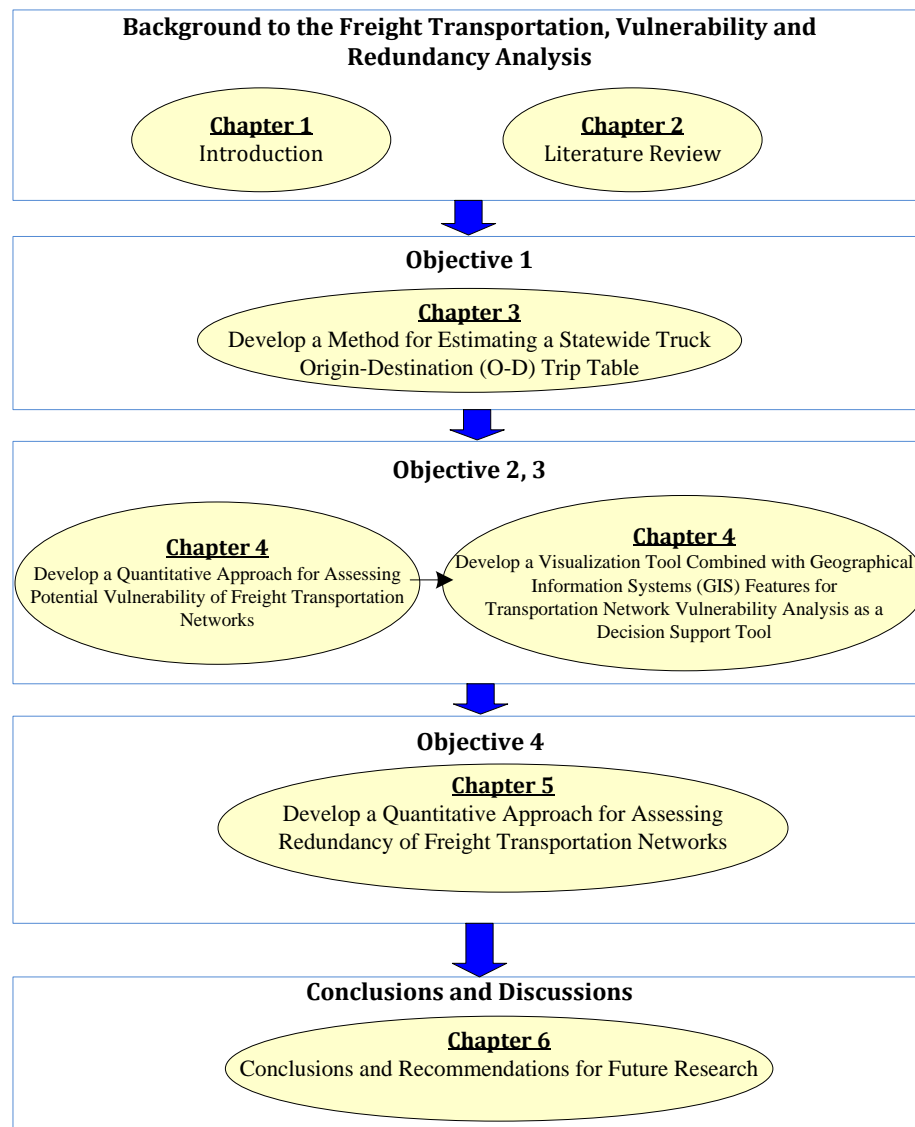
Fig. 1.1 Dissertation organization

Chapter 2 provides the relevant literature review on statewide truck O-D estimation modeling, transportation network vulnerability analysis, and transportation network redundancy analysis. The following three chapters (i.e., Chapters 3, 4 and 5) are the main contributions of this dissertation, which consist of three technical papers. Chapter 3 provides a two-stage approach to estimate a statewide truck origin-destination (O-D) trip table. Chapter 4 presents the development of a decision support system tool for assessing vulnerability of freight transportation networks. Chapter 5 develops quantitative measure for evaluating the redundancy of freight transportation networks. Concluding remarks and future research directions are summarized in Chapter 6.

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CHAPTER 2

LITERATURE REVIEW

This chapter reviews the relevant literature based on the proposed research framework. Section 2.1 reviews the freight transportation demand modeling focusing on truck O-D estimation modeling approaches. Section 2.2 reviews transportation network vulnerability analysis approaches. Section 2.3 reviews some useful concepts for assessing resiliency of transportation networks with a focus on redundancy analysis.

2.1   Truck origin-destination (O-D) estimation modeling

State-of-the-practice in truck freight modeling techniques can be classified broadly into the following eight categories based on objective, methodology, and data requirements: (1) link-based factoring techniques; (2) origin-destination (O-D) factoring, (3) three-step freight truck models; (4) four-step commodity flow models; (5) economic activity models; (6) hybrid models; (7) logistics/supply chain models; and (8) tour-based models (Fischer *et al*., 2005). Holguín-Veras and Thorson (2000), however, also summarized different ways that could be used for modeling freight demand and divided them into two major modeling platforms: (1) trip-based modeling, and (2) commodity-based modeling. Fig. 2.1 depicts the outline of these two approaches. This section provides a literature review of the research literature based on these two concepts:

2.1.1   *Trip-based modeling*

For trip-based modeling, the model has three major components: trip generation, trip distribution, and traffic assignment. The trip-based model begins with trip generation.
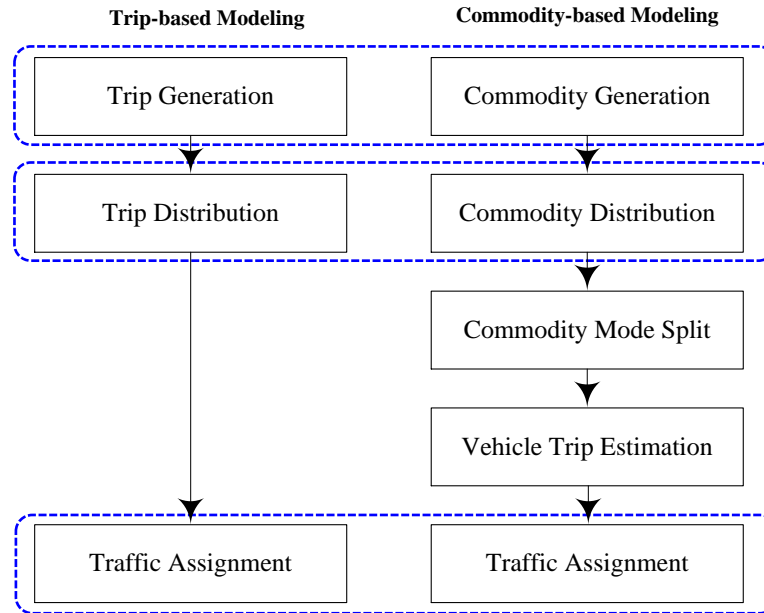
Fig. 2.1 Trip-based and Commodity-based approaches
(modified from Holguín-Veras and Thorson, 2000)

In this step, the regression models for trip production and trip attraction are estimated in conjunction with the land use and the socio-economic characteristics for each Traffic Analysis Zones (TAZ). The next step is trip distribution, which is accomplished through spatial interaction model (i.e., gravity models or growth factor methods). The last step is to assign the traffic to the network. This model is also known as a three-step model as the mode choice has been already made in the prior step.

The current practice in estimating those models table is through the use of the truck trip rates estimated in the Quick Response Freight Manual (QRFM) II developed by Cambridge Systematics (2007). The QRFM provides truck trip generation rates based on the survey data collected from Phoenix, Arizona. Using the trip rates to reflect the trip-making propensity of the land use configuration is a common practice, and provides an economical and reasonable estimate when planning resources are limited.

Many researchers have demonstrated the estimation of truck O-D trip table could be achieved using secondary data sources based on trip-based modeling. Tamin and Willumsen (1989) introduced a *three-step* model to estimate freight demand from observed traffic count data. They used two types of gravity models in the trip distribution step including the Gravity Model (GR) and the Gravity-Opportunity Model (GO). They proposed non-linear least square and maximum likelihood estimation methods to ensure that the models estimate link flows as close as possible to the observed data. List and Turnquist (1994) proposed an O-D estimation method to synthesize the truck flow pattern from the observed truck counts for some links and cordon lines. This method was based on a linear programming model that attempts to minimize the weighted sum of the residual between the estimated and observed values, given the user-defined choice of variables for the truck classes and network zone structure. The link-use coefficients for each O-D pair were calculated with the help of a probabilistic path assignment algorithm.

Later, List *et al*. (2002) used a similar technique to estimate a large-scale truck O-D trip in the New York region. The model was implemented in a two-step process: the first step is to estimates trip generation and attraction and the second step is to use the link-use coefficients based on a multi-path traffic assignment. Crainic *et al*. (2001) used the bi-level matrix optimization program to adjust the target freight demand matrices such that the differences between the observed and assigned truck flows in the upper level are minimized. The lower level for this bi-level program is the *system optimum* (SO) traffic assignment. They implemented the proposed method in the Strategic Planning of Freight transportation (STAN) software, an interactive-graphic transportation planning package for multimodal multiproduct freight transportation. The main

advantage of the trip-based modeling method is that it typically requires less data (i.e., only truck traffic counts) with some existing planning data (e.g., partial or full size of target trip table) to estimate an O-D matrix. However, the main disadvantage of the trip-based modeling method is that it tends to overlook the behavioral characteristics of commodity flows in the urban and regional models. Holguín-Veras *et al.* (2001) noted that trip-based models have a limited range of applicability to account for major changes of those study areas such as changes in land use and it could be difficult to model multimodal systems using this approach.

2.1.2   Commodity-based modeling

The commodity-based modeling method, on the other hand, uses the commodity flows to estimate truck flows produced and attracted by each TAZ. In the U.S., the FAF estimates commodity flows over the national highway networks, waterways and rail systems among states and regions. The current version of the FAF commodity O-D database (FAF version 3) provides estimates of commodity flows for the base year 2007 and the forecast years from 2010 to 2040 with a five-year interval. Note that the FAF commodity O-D database was developed using the 2007 Commodity Flow Survey (CFS) and other public data sources. The commodity flows in tonnage estimated in FAF are disaggregated from the state to the zonal level to reflect the production and attraction zones in the state. The commodity flows are then converted to truck trips using truck payload equivalent (TPE) factors for the truck traffic assignment procedure.

Because the CFS database is based on survey data established through a shipper-based survey, the commodity-based models thus have more potential to capture the fundamental behavioral characteristics of commodity flows. Sorratini and Smith (2000),

for example, developed a statewide truck trip model using commodity flow data obtained from the CFS database and improved the estimation using the input-output (I-O) economic data. Al-Battaineh and Kaysi (2005) further used the genetic algorithm (GA) to find the best O-D matrix, that when assigned trips from that O-D matrix to the network, gives the minimum deviation between observed and estimated data. Trip production and trip attraction derived from the trip generation step were also used to preserve the spatial distribution of the commodity flow pattern. The relevant issue for this approach is that GA cannot guarantee to find the global optimum or even a near-optimal solution. Stefan *et al*. (2005) noted that that it is difficult to obtain the I-O data for regional and urban areas.

The commodity-based approach is often used in the statewide and regional practices. Zhang *et al*. (2003), for instance, estimated the intermodal freight flow patterns of highway, railway, and waterway networks for the state of Mississippi using the public domain data and CFS database. They further developed the simulation model to assess freight operations and the effects of modal shift (i.e., from truck to intermodal barge/truck). Liedtke (2006) and Wisetjindawat *et al*. (2006) used microsimulation models to replicate the commodity movements and assess different scenarios of urban freight distribution. This approach can further combine with the logistics supply chain models for modeling the regional freight network traffic Although this approach provides a much finer resolution of truck traffic flows over time periods, this technique is usually data demanding, computationally expensive and may be more suitable for assessing truck operations of urban freight traffic, instead of regional freight traffic for strategic planning.

While the commodity-based models have more advantages than the trip-based

models as they can capture more accurately the fundamental economic mechanisms of freight movements, a truck O-D trip table estimated from the commodity-based method often overlooks the non-freight truck trips (e.g., commercial truck or empty truck trips). Hybrid models are often used to bridge the modeling gap of trip-based and commodity-based models. Holguín-Veras and Patil (2008) developed a multi-commodity O-D estimation model that combined two submodels: (1) a commodity-based model, and (2) a complementary model of empty truck trips. The findings of this study highlights the significant benefits of considering an empty truck trip model in the estimation process as it can improve their ability to replicate the observed traffic counts. The hybrid approach was also adopted in the Southern California Association of Government (SCAG)'s truck demand model. Hybrid models forecast Internal-Internal truck trips through the use of a trip based model and forecast the external truck trips through the use of a commodity flow surveys. The hybrid model has great flexibility to incorporate external trips that can be analyzed from special trip generators, which are, for instance, truck trips from warehouses and distribution centers or additional freight surveys. Some of freight modeling approaches including trip-based, commodity-based, and hybrid models are summarized in Table 2.1.

2.2   Transportation network vulnerability analysis

Transportation network vulnerability analysis has emerged as an important topic. There are no universal definitions of quantitative measure for assessing transportation network vulnerability, but the seminal works and concepts of risk, reliability, and vulnerability with respect to the road transportation system are firstly discussed in Berdica (2002), please refer to Section 1.2 for her definition.

Table 2.1: Freight demand modeling approaches, methods, and data sources

Authors	Modeling Approaches		Methods	Data sources
	Trip-based	Commodity-based		
List and Turnquist (1994)	●		Linear programming model	observed truck counts for some links and cordon lines
Sorratini and Smith (2000)		●	I-O model	CFS, TRANSEARCH
List *et al.* (2002)	●		Linear programming model	Observed truck counts for some links and cordon lines
Zhang *et al.* (2003)		●	Planning and simulation models	CFS, TRANSEARCH, intermodal databases
Al-Battaineh and Kaysi (2005)		●	I-O model, Genetic Algorithm	commodity flows, observed truck traffic
Liedtke (2006), Wisetjindawat *et al.* (2006)		●	Microsimulation	commodity flow surveys
Fischer *et al.* (2005)	◖	◗	Hybrid model	shipper and receiver surveys (for internal trips), commodity flow surveys (for external trips)
Houlguin-Veras and Patil (2008)	◖	◗	Hybrid model, Minimize least square	multi-commodity flows, estimated empty truck trips, observed truck traffic

Berdica (2002) suggested that vulnerability should include both the *probability* and *consequences* of an incident occurring. Hence, the reduction of vulnerability is, in a way, similar to the reduction of risk in risk analysis. The similar views of using concept

of risk to assess vulnerability are proposed by, e.g., Dalziell and Nicholson, 2001; Jenelius *et al*., 2006; Jenelius, 2010a. Dalziell and Nicholson (2001), for instance, used the concept of risk to assess the *system-wide effects* of road closure in New Zealand. In the assessment process, risks caused by bad weather, natural disasters, and traffic accidents were evaluated in terms of the frequency of occurrence and duration of road closure, which are characteristics of abnormal events that are normally being ignored by the traditional reliability and vulnerability analysis. Jenelius (2010a) described that *vulnerability is risk*. Jenelius posed three fundamental questions: (1) what can happen? (2) how likely is it that will happen?, and (3) if it does happen, what are the consequences? The answers of these triplets represent the concept of risk, each consisting of a description of a particular scenario, the probability of that scenario occurring, and the impact of the scenario, thus provide the basics of vulnerability assessment.

Berdica suggested a sequential definition of vulnerability in the transportation network as a wheel concept, as shown in Fig. 2.2. Using the framework in Fig. 2.2, Berdica provided different operational definitions required to model vulnerability in a road network. The framework by Berdica (2002) is useful in analyzing vulnerability, however, it does not provide the necessary basis for comparison of various threats and the tradeoffs among potential response measures. Network vulnerability can then be defined as the susceptibility to disruptions that can cause significant reduction in network services.

Fig. 2.2 Vulnerability in the road transportation system: wheel of concepts
(Source: Berdica, 2002)

Services of transportation networks are to provide a means for moving passengers and goods to different places at different times. Transportation network vulnerability can be regarded as a problem of reduced *network performance* or *efficiency* due to different disruptions. A few approaches have been used to measure network vulnerability. In our view, they are classified into four categories, as follows.

2.2.1   Connective vulnerability

In D'Este and Taylor (2003), vulnerability is related to the consequences of "*freak events*," which cause link failure, irrespective of the probability of such failures or freak events. Two definitions of vulnerability for the network analysis were used in D'Este and Taylor's study. The first definition is the *connective vulnerability*, focusing on connectivity between two nodes and the second one is the *access vulnerability* of a node. For example, if one of the links on the preferred route between Perth and Adelaide in the Australian network fails, the consequence in that particular event is that travelers need to make a detour of 5,000 kilometers.

Connective vulnerability considers the consequence of network degradation. D'Este and Taylor (2003) used the probability-based approach (i..e, Bell's method (Bell, 1995)) to scan the '*weak spots*' in the UK national rail network, where failure of some part of the transportation infrastructure can have adverse consequences on increased travel distance and travel time. Kurauchi *et al.* (2009) proposed the method to identify the critical link from the network topology, called *connectivity vulnerability*. The number of distinct paths with acceptable travel time between each origin-destination (OD) pair is used to measure the connectivity of that OD pair (i.e., similar to the concept of *k*-edge connectivity). Though connective vulnerability measures are intuitive, and easy to implement in different network topologies, they have been criticized for ignoring the demand-supply relationship (i.e., the congestion effect) and the behavior of travelers.

2.2.2   *Travel time vulnerability*

The network performance can be evaluated based on an increase in the generalized travel time or cost when one or more links are disrupted. To avoid the enumeration of the extremely large number of scenarios of potential network failures, Lleras-Echeverri and Sanchez-Silva (2001) proposed a Critical-Scenario (CS)-based approach, which restricts the study to a subset of failure scenarios that are more likely to be critical. Unlike D'Este and Taylor's first-order method that only considers one-link failure scenarios, the CS-based approach makes it possible to analyze all orders in a large-scale network.

Nagurney and Qiang (2007) stated that although the topological structure of a network has an obvious impact on network performance and vulnerability, network flow allocation is also an important indicator, as are the induced (travel) costs and travel

behavior of users in the network. To address the aforementioned issues, they developed a network efficiency measure that captures flows, costs, and routing behavior. The N-Q measure for a given graph, *G*, and a vector of O-D demands, *d*, can be defined as:

$$E_{N-Q}(G,d) = \sum_r \sum_{s \neq r} \frac{d_{rs}/c_{rs}}{N_{rs}}, \tag{2.1}$$

where d_{rs} and c_{rs} are the travel demand and the minimum travel time associated with O-D pair (*r, s*), and N_{rs} is the number of O-D pairs in the network. Typically, link importance is measured by removing one link at a time out of a network, assessing the network performance based on the damaged condition, and then examining the decreased network performance. A higher decreased network performance indicates a higher importance of the removed link. The importance of link *a* based on the N-Q measure is: $I_{N-Q}(a) = \left(E_{N-Q}(G,d) - E_{N-Q}(G-a,d)\right)/E_{N-Q}(G,d)$, where *G-a* is the resulting network after link *a* is removed from network *G*. Furthermore, many researchers have also used a similar approach to examine link importance in transportation networks. For example, Scott *et al*. (2006) proposed the *Network Robustness Index* (NRI) to identify the critical highway segments. According to their study, a critical link is defined as a link whose disruption causes a substantial increase in system-wide travel time derived based on the DUE principle. The NRI of link *b*, *NRI(b)*, can be expressed as:

$$NRI(b) = \sum_{a \in G-b} c_a^b x_a^b - \sum_{a \in G} c_a x_a, \tag{2.2}$$

where c_a is the equilibrium travel time of link *a*, x_a is the flow on link *a*, c_a^b and x_a^b are the travel time and flow of link *a* after link *b* is removed from the network. Sullivan *et al*. (2010) further enhanced this index to the *Network Trip Robustness (NTR) index*, which

provides a scalable measure for network robustness that can be used to compare different size of network with different levels of demands and connectivity. Jenelius *et al.* (2006) and Jenelius (2009) also developed a link importance index, which defines the increase of generalized travel cost when links are removed from a network. They proposed three importance measures: (1) global importance, (2) demand-weighted importance, and (3) unsatisfied demand-related importance. The global importance (I_{net}^{glob}) and the demand-weighted importance (I_{net}^{dem}) can be expressed as follows:

$$I_{net}^{glob}(a) = \sum_{r}\sum_{s\neq r}\frac{c_{rs}^{a}-c_{rs}^{0}}{N_{rs}(N_{rs}-1)}, \tag{2.3}$$

$$I_{net}^{dem}(a) = \frac{\sum_{r}\sum_{s\neq r}d_{rs}(c_{rs}^{a}-c_{rs}^{0})}{\sum_{r}\sum_{s\neq r}d_{rs}}, \tag{2.4}$$

where c_{rs}^{a} represents a finite and positive travel cost (can be zero) between O-D pair (*r, s*) when link *a* is removed from the network, c_{rs}^{0} represents the travel cost between O-D pair (*r, s*) of the undamaged network (i.e., initial condition of network). For some other links with infinite travel costs after removing them, the importance for those links is represented using the concept of unsatisfied demand or number of trips that cannot reach to a destination (i.e., the unsatisfied demand-related importance).

2.2.3 Access vulnerability

Accessibility is determined by the spatial distribution of potential destinations, the ease of reaching each destination, and the magnitude, quality, and character of the activities found there (Handy and Niemeier, 1997). Chang and Nojima (2001) applied the distance-based accessibility measure (i.e., without congestion effects) to assess the

transportation system performance for an earthquake scenario. Chang (2003) also applied the distance-based accessibility measure for evaluating restoration strategies after the Hansin earthquake. The travel time-based accessibility measure (i.e., with congestion effects) was used to assess potential bridge damage in the Seattle area. Sohn (2006) employed the weighted accessibility measure by distance and traffic volume to prioritize the retrofit plans for highway links under the event of a flood disaster. The accessibility index of the county and state level as a whole is determined before and after the single link failures in the network, especially within the floodplain. With different criteria between distance-only and distance-traffic volume, the critical link is identified differently. The retrofit priority then depends on what criterion is chosen. Taylor *et al.* (2006) define the access vulnerability by the following:

- a network *node* is *vulnerable* if loss (or substantial degradation) of a small number of links significantly diminishes the accessibility of the node

- a network *link* is *critical* if loss (or substantial degradation) of the link significantly diminishes the accessibility of the network or of particular nodes,

Taylor *et al.* (2006) adopted the Hansen integral accessibility index and Accessibility Remoteness Index of Australia (ARIA) remoteness index to determine critical section(s) in the Australian national roadway network. Accordingly, the longer the travel distance between two cities, the lower the accessibility index between them. Similarly, Taylor (2008) used the accessibility framework to assess the critical locations in urban road networks, and the development and application of diagnostic tools that will allow urban road system managers to anticipate potential vulnerabilities to incident-related congestion and take proactive action to avoid congestion rather than react to it.

Chen *et al*. (2007) developed a *network-based accessibility* measure using a combined travel demand model for assessing vulnerability of degradable transportation networks. They calculated the long term effects of network disruptions as the decrease of a utility-based accessibility measure derived from individual responses across different travel choice dimensions.

2.2.4   *Network flow and encountered vulnerability*

Network flow is one performance indicator in a transportation network. Many substantial studies from this field have been applied to identify the most critical node and link in transportation networks. Church *et al*. (2004) applied the *network interdiction model* to identify the critical facility that gives the worst case of loss when it is removed from a network. Matisziw *et al*. (2007) developed mathematical models called the *p*-Cutset Problem (PCUP) which are capable of producing the upper and lower bounds (i.e., maximum and minimum flow losses or reliability envelope) on the loss of connectivity resulted from interdictions. The reliability envelope is useful in practice as it can assist decision makers prioritizing and protecting critical facilities during disastrous events.

An alternative approach to measure transportation network vulnerability is to use game theory, see studies by Bell and Cassir (2002), Bell (2003), and Murray-Tuite and Mahmassani (2004). They developed a mixed strategy game between two players who could take on the role of either the attackers who seek to maximize the total network travel time or cost, travelers who seek to minimize their expected travel time, or network planners who seek for strategies to defend against the attackers. Equilibrium is reached when no individual can improve their benefit by unilaterally changing their strategies. The critical links are identified as a consequence of the game.

In summary, existing transportation network vulnerability measures are classified according to type of measures: network topological property, travel time and generalized travel cost, accessibility and network flow, respectively. However, they heavily focus on passenger transportation. Thus, there is currently very little research focusing on vulnerability analysis for freight transportation networks. Some of transportation vulnerability approaches, performance indicators and aspects for users and planners are summarized in Table 2.2.

2.3   Transportation network redundancy analysis

Various conceptual frameworks and measures have been proposed for analyzing transportation network resiliency, e.g., Caplice *et al*. (2008), Goodchild *et al*. (2009), Ortiz *et al*. (2009), Ta *et al*. (2009), Cox *et al*. (2011), Ip and Wang (2011), Urena *et al*. (2011), Adams *et al*. (2012), Faturechi and Miller-Hooks (2013), and Omer *et al*. (2013). Engineers and social scientists at the Multidisciplinary Center for Earthquake Engineering Research (MCEER) have proposed a framework for defining resiliency (Bruneau *et al*., 2003). This study characterizes resiliency based on the four "Rs" concept:

- Robustness refers to "strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function";

- Redundancy refers to "the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of function";

Table 2.2: Transportation network vulnerability analysis approaches

Authors	Vulnerability Categories	Performance Indicators	Vulnerability Aspects for	
			User	Planner
Lleras-Echeverri and Sanchez-Silva (2001)	Travel time	Total generalized travel costs	Good Usefulness	Good Usefulness
D'Este and Taylor (2003)	Connectivity	Detour distance, number of paths	Good Usefulness	Good Usefulness
Bell and Cassir (2002), Bell (2003)	Game theory	Total network travel time or cost/ expected travel time	Minimal Usefulness	Good Usefulness
Scott *et al*. (2006), Sullivan *et al*. (2010)	Travel time	Total network travel time or costs	Minimal Usefulness	Good Usefulness
Sohn (2006)	Accessibility	Accessibility of the county and state levels	Good Usefulness	Good Usefulness
Jenelius *et al*. (2006), Jenelius (2009)	Travel time	Generalized travel costs, unsatisfied demand	Good Usefulness	Good Usefulness
Taylor *et al*. (2006)	Accessibility	Accessibility and remoteness index based on distance	Good Usefulness	Good Usefulness
Chen *et al*. (2007)	Accessibility	Utility-based accessibility measure	Good Usefulness	Good Usefulness
Nagurney and Qiang (2007)	Travel time	Demand-weighted travel costs	Minimal Usefulness	Good Usefulness
Matisziw *et al*. (2007)	Network flow	O-D flow losses	Minimal Usefulness	Good Usefulness
Kurauchi *et al*. (2009)	Connectivity	Number of distinct paths	Good Usefulness	Good Usefulness

- Resourcefulness refers to "the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis"; and

- Rapidity refers to "the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption."

It is clear that redundancy is another concept that can help address system vulnerability. A few concepts of redundancy are reviewed as follows.

2.3.1 *Some useful redundancy concepts*

The concept of redundancy has been studied in different disciplines including reliability engineering, water distribution system, computer network, the internet, and so on. The Webster/Merriam Dictionary (2012) gives a general definition of redundancy (or state of redundant) as: (1) *exceeding what is necessary or normal,* or (2) *serving as a duplicate for preventing failure of an entire system upon failure of a single component*. In reliability engineering, redundancy is the existence of more than one means for accomplishing a given function, and each means of accomplishing the function is not necessarily identical (O'Connor, 2010). Redundancy in water distribution system is defined as the existence of alternative pathways from the source to demand nodes or excess capacity in normal operating conditions when some components of the system become unavailable (Kalungi and Tanyimboh, 2003). According to the above definition, there are two types of redundancy measures: (a) active redundancy, and (b) standby redundancy. The active redundancy is the redundancy where all redundant items are operating simultaneously rather than being switched on when needed. On the other hand, the standby redundancy is the redundancy where the alternative means of performing the

function is inoperative until needed and is switched on upon failure of the primary means of performing the function. In structural engineering, redundancy is the ability of a structural system to redistribute stresses to its members/connections and thereby ensuring the safety of structural systems. According to Fang and Fan (2011), the redundant structures can assist in: (1) enhancing the safety margin/reliability of a structure in its intact state; and (2) mitigating the sensitivity/vulnerability of the structure to localized damage under an accidental situation.

Redundancy is also a well-known concept in computer science, especially for the Internet. The Internet was designed to make use of the redundancy embedded in the network structure (Wheeler and O'Kelly, 1999). When the primary network encounters a disruptive event (e.g., natural disaster or man-made incident), the internet service providers (ISPs) automatically implement rerouting strategy to reroute traffic to redundant connections. Typically, the goal of a redundant internet network aims to minimize the *downtime* (or negative impact) to ensure service reliability. In addition, many businesses today implement a *backup system* (i.e., secondary connection) which is totally independent of the primary network to reduce the outage effect. In the context of graph theory, various measures were introduced to analyze network efficiency by expressing the relationship between the network structure and its properties. Rodrigue and Ducruet (2009) summarized some useful indices for measuring network efficiency. For example, they used the alpha index to measure network connectivity and network redundancy (i.e., alpha index$=(e-v+1)/(2v-5)$, where e is the number of links, and v is the number of nodes in a network). The alpha index, ranging between 0 and 1, indicates the degree of network connectivity. An alpha value of 1 represents a highly redundant

network, while a value of 0 indicates redundancy is non-existence. In logistics and supply chain, Sheffi and Rice. (2005) suggested that flexibility and redundancy are key factors to achieve resiliency.   The redundancy is related to the concept of safety stock, underutilized capacity or inventory in reserve to be used in case of disruption, while flexibility, in their perspective, can help a company (or a supplier) not only to withstand significant disruption but also respond to demand fluctuations, thus increasing its competiveness.

2.3.2   *Redundancy in transportation networks*

Berdica (2002) firstly developed a framework and basic concepts for vulnerability and many neighboring terms such as resiliency and redundancy. According to Berdica (2002), redundancy is *the existence of numerous optional routes/means of transport between origin and destinations can result in less serious consequences in case of a disturbance in some part of the system*. From her viewpoint, redundancy is related to the system diversity that can be used to handle a network disturbance. Few researchers have introduced measures for assessing the resiliency of transportation networks and redundancy is one of those measures. For example, Godschalk (2003) and Murray-Tuite (2006) defined redundancy as the number of functionally similar components which can serve the same purpose, and hence the system does not fail when one component fails. A relevant concept of redundancy is *diversity*, which refers to a number of functionally different components that protect the system against various threats (e.g., alternative transport modes). Similarly, Goodchild *et al*. (2009) introduced redundancy as one of the desired properties of freight transportation resiliency. They defined redundancy as the availability of multiple alternate routing options in the freight transportation network.

Jenelius (2010b) recently proposed the concept of redundancy importance to consider the importance of links as backup alternatives when other links in the network are disrupted. Two measures (i.e., flow-based and impact-based) were proposed to quantify the redundancy importance. The flow-based measure considers a net traffic flow that is redirected to the backup links and the impact-based measure considers an increased travel time (cost) due to the rerouting effect. However, these two measures assess only the localized redundancy importance of a transportation network. In other words, they are not able to capture the diversity of alternatives, an important property for measuring network redundancy. In our study, we propose a two-dimensional approach to assess redundancy: (1) *route diversity*, and (2) *network spare capacity*. We argue that the *diversity of available routes and modes* when the primary choice is inoperative needs to be explicitly considered in the redundancy characterization. However, the route diversity alone may not be a sufficient measure of redundancy as it lacks the interaction between transport demand and supply (i.e., congestion effect due to limited network capacity). Congestion effect and freight shippers' decisions in route and mode choices are two critical characteristics of freight transportation networks. In order to adequately capture these two characteristics, network spare capacity should also be explicitly considered in freight network redundancy characterization.

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CHAPTER 3

A TWO-STAGE APPROACH FOR ESTIMATING A STATEWIDE TRUCK ORIGIN-

DESTINATION TRIP TABLE: A CASE STUDY IN UTAH

Abstract

This research proposes a two-stage approach to estimate a statewide truck origin-destination (O-D) trip table. The proposed approach is supported by two sequential stages: one estimates the commodity-based truck O-D trip tables primarily derived from the commodity flow database, and the other refines them using the observed truck counts to reproduce the better matches. The first stage uses a national commodity flow data from the Freight Analysis Framework Version 3 (FAF3) database to develop a commodity-based truck trip table. The second stage uses the path flow estimator (PFE) concept to refine the truck trip table obtained from the first stage using the truck counts from the statewide truck count program. The model allows great flexibility of incorporating data at different spatial levels for estimating truck O-D trip tables. A case study is conducted using the Utah statewide freight transportation network to demonstrate how the proposed approach can be implemented in practice.

3.1   Introduction

Statewide models including passenger and freight movements are frequently used for supporting numerous statewide planning activities. Many states use them for traffic impact studies, air quality conformity analysis, freight planning, economic development studies, project prioritization, and many other planning needs (Horowitz, 2006). According to the latest figures from FHWA (2009) and the U.S. Census Bureau (2010, 2012) the United States (U.S.) transportation system transported a total of 17.6 billion

tons per year in 2011 to serve almost 117 million households, 7.4 million business establishments, and 89,100 units of government. The importance of truck demand has been increased in the statewide planning process because of its strong influence on the economy of the states and the nation overall. Truck is the dominant mode of freight transportation, with the industry hauling of 11.9 billion tons in 2011, equating to approximately two-thirds (i.e., 67%) of all freight transported in the U.S. (FHWA, 2009).Truck transportation will continue to grow over the next decade as the steady growth in the U.S. economy, an increase in international merchandise trade, improvements in freight sector productivity, and the availability of demand of an extensive multimodal transportation network (Bureau of Transportation Statistics, 2004). According to the Freight Analysis Framework database, truck shares 75% of the domestic freight shipments and it will be stable from 2007 to 2040. However, freight transportation capacity especially the roadway transportation is expanding too slowly to keep up with demand (Cambridge Systematics, 2005). This imbalance growths could significantly contribute to congestion at highway segments, interchanges, and highway bottlenecks (i.e., locations where are physically narrow and/or congested) and hence are very susceptible to incidents and disruptions. Therefore, the truck demand is an important component in the statewide transportation planning and the forecast demand can support the long-term strategies for the infrastructure management and investment decisions.

The current practice in estimating a statewide truck origin-destination (O-D) trip table is through using the truck trip rates estimated in the Quick Response Freight Manual (QRFM) developed by Cambridge Systematics (2007), or using a commercial freight database (i.e., Transearch developed by IHS Global Insight, Inc.). However, because of

the nature of the shared databases, the state Department of Transportation (DOT) has to spend tremendous efforts to improve the accuracy of the estimations to match the local observations (e.g., truck counts, vehicle-miles of travel (VMT), etc.). The calibration process is usually a lengthy process and requires specialized technical staffs to operate. In addition, commercial freight databases are typically proprietary, not available for public access. Many small and medium-sized Metropolitan Planning Organizations (MPOs) usually do not have sufficient resources to conduct freight surveys, nor to house technical staffs to develop the freight demand model. Many existing models, hence, overlook this component, or just simply make assumptions that freight trips follow some behavioral mechanism similar to passenger trips, that is, truck traffic is estimated as a function of passenger-car traffics (Ogden, 1992). This could be a potential weakness of truck demand modeling in the statewide model where truck flow characteristics have been determined by other contributing factors such as location factors (i.e., places of production and market), physical factors (i.e., method that goods can be transported: in bulk, tank, flat bed, or refrigerated container), geographical factors (the location and density of population may influence the distribution of end products) and so on (de Dios Ortuzar and Willumsen, 2002).

Many different approaches have been attempted in the literature to develop statewide freight models. Holguín-Veras and Thorson (2000) summarized different ways that could be used for modeling freight transportation demand, and divided them into two major modeling platforms: trip-based modeling and commodity based modeling. For trip-based modeling, the model has three major components including trip generation, trip distribution, and traffic assignment. Trip-based modeling does not need a modal split step

as it assumes mode selections have already been done. List *et al*. (2002), for instance, used the trip-based modeling method to estimate a truck O-D trip table from partial and fragmentary truck observations in the New York region. The main advantage of trip-based modeling method is that it typically requires less data (i.e., only truck traffic counts) to reproduce an O-D matrix. However, trip-based modeling tends to overlook the behavioral characteristics of commodity flows. Commodity-based modeling method, on the other hand, uses the commodity flows to estimate truck flows produced and attracted by each zone in the study area. Sorratini and Smith (2000), for example, developed a statewide truck trip model using commodity flow data obtained from the commodity flow survey (CFS) and improve the estimation using the input-output (I-O) economic data. Although the commodity-based models have more advantages than trip-based models as they can capture more accurately the fundamental economic mechanisms of freight movements, yet a truck O-D trip table estimated from this method often overlooks the non-freight truck trips (e.g., light commercial truck or empty truck trips).

To fill this modeling gap, this research proposes an alternative approach called a two-stage approach to estimate a statewide truck O-D trip table. The proposed approach is supported by two sequential stages: one estimates the commodity-based truck O-D trip tables primarily derived from the commodity flow database, and the other refines them using the observed truck counts to reproduce the better matches using the concept of path flow estimator (PFE). The proposed approach uses the secondary data sources available for public and research access such as the Freight Analysis Framework (FAF) database, statewide traffic counts, and socioeconomic and landuse data to estimate statewide network truck traffic. A case study using the Utah statewide freight transportation

network is conducted to demonstrate the application of the proposed method. This chapter is divided into five subsections. Section 3.2 provides an overview and review of methods for estimating truck O-D trip table including commodity-based and trip-based models. Section 3.3 explains the approach for estimating the statewide truck O-D trip table. Section 3.4 presents the analysis and findings in Utah statewide freight transportation network. And finally in section 3.5, we conclude and discuss the findings and future research direction.

3.2   Literature review

Holguín-Veras and Thorson (2000) summarized different ways that could be used for modeling freight demand and divided them into two major modeling platforms: (1) Trip-based modeling, and (2) Commodity-based modeling. This section provides a literature review of the research literature based on these two concepts:

3.2.1   Trip-based modeling

For trip-based modeling, the model has three major components: trip generation, trip distribution, and traffic assignment. The trip-based model begins with trip generation. In this step, the regression models for trip production and trip attraction are estimated in conjunction with the land use and the socio-economic characteristics for each Traffic Analysis Zones (TAZ). The next step is trip distribution, which is accomplished through spatial interaction model (i.e., gravity models or growth factor methods). The last step is to assign the traffic to the network. This model is also known as a three-step model as the mode choice has been already made in the prior step.

The current practice in estimating those models table is through the use of the truck trip rates estimated in the Quick Response Freight Manual (QRFM) II developed by

Cambridge Systematics (2007). The QRFM provides truck trip generation rates based on the survey data collected from Phoenix, Arizona. Using the trip rates to reflect the trip-making propensity of the land use configuration is a common practice, and provides an economical and reasonable estimate when planning resources are limited.

Many researchers have demonstrated the estimation of truck O-D trip table could be achieved using secondary data sources based on trip-based modeling. Tamin and Willumsen (1989) introduced a *three-step* model to estimate freight demand from observed traffic count data. They used two types of gravity models in the trip distribution step including the Gravity Model (GR) and the Gravity-Opportunity Model (GO). They proposed non-linear least square and maximum likelihood estimation methods to ensure that the models estimate link flows as close as possible to the observed data. List and Turnquist (1994) proposed an O-D estimation method to synthesize the truck flow pattern from the observed truck counts for some links and cordon lines. This method was based on a linear programming model that attempts to minimize the weighted sum of the residual between the estimated and observed values, given the user-defined choice of variables for the truck classes and network zone structure. The link-use coefficients for each O-D pair were calculated with the help of a probabilistic path assignment algorithm.

Later, List *et al*. (2002) used a similar technique to estimate a large-scale truck O-D trip in the New York region. The model was implemented in a two-step process: the first step is to estimates trip generation and attraction and the second step is to use the link-use coefficients based on a multi-path traffic assignment. Crainic *et al*. (2001) used the bi-level matrix optimization program to adjust the target freight demand matrices such that the differences between the observed and assigned truck flows in the upper

level are minimized. The lower level for this bi-level program is the *system optimum* (SO) traffic assignment. They implemented the proposed method in the Strategic Planning of Freight transportation (STAN) software, an interactive-graphic transportation planning package for multimodal multiproduct freight transportation. The main advantage of the trip-based modeling method is that it typically requires less data (i.e., only truck traffic counts) with some existing planning data (e.g., partial or full size of target trip table) to estimate an O-D matrix. However, the main disadvantage of the trip-based modeling method is that it tends to overlook the behavioral characteristics of commodity flows in the urban and regional models. Holguín-Veras *et al.* (2001) noted that trip-based models have a limited range of applicability to account for major changes of those study areas such as changes in land use and it could be difficult to model multimodal systems using this approach.

3.2.2   *Commodity-based modeling*

The Commodity-based modeling method, on the other hand, uses the commodity flows to estimate truck flows produced and attracted by each TAZ. In the U.S., the FAF estimates commodity flows over the national highway networks, waterways and rail systems among states and regions. The current version of the FAF commodity O-D database (FAF version 3) provides estimates of commodity flows for the base year 2007 and the forecast years from 2010 to 2040 with a five-year interval. Note that the FAF commodity O-D database was developed using the 2007 Commodity Flow Survey (CFS) and other public data sources. The commodity flows in tonnage estimated in FAF are disaggregated from the state to the zonal level to reflect the production and attraction zones in the state. The commodity flows are then converted to truck trips using truck

payload equivalent factors (TPEF) for the truck traffic assignment procedure.

Because the CFS database is based on survey data established through a shipper-based survey, the commodity-based models thus have more potential to capture the fundamental behavioral characteristics of commodity flows. Sorratini and Smith (2000), for example, developed a statewide truck trip model using commodity flow data obtained from the CFS database and improved the estimation using the input-output (I-O) economic data. The similar technique was also adopted by Fischer *et al*. (2000) for estimating the heavy-duty truck O-D trip table for the Southern California Association of Government (SCAG). Al-Battaineh and Kaysi (2005) further used the genetic algorithm (GA) to find the best O-D matrix, that when assigned trips from that O-D matrix to the network, gives the minimum deviation between observed and estimated data. Trip production and trip attraction derived from the trip generation step were also used to preserve the spatial distribution of the commodity flow pattern. The relevant issue for this approach is that GA cannot guarantee to find the global optimum or even a near-optimal solution. Stefan *et al*. (2005) noted that that it is difficult to obtain the I-O data for regional and urban areas.

The commodity-based approach is often used in the statewide and regional practices. Zhang *et al*. (2003), for instance, estimated the intermodal freight flow patterns of highway, railway, and waterway networks for the state of Mississippi using the public domain data and CFS database. They further developed the simulation model to assess freight operations and the effects of modal shift (i.e., from truck to intermodal barge/truck). Liedtke (2006) and Wisetjindawat *et al*. (2006) used microsimulation models to replicate the commodity movements and assess different scenarios of urban

freight distribution. Although this approach provides a much finer resolution of truck traffic flows over time periods, this technique is usually data demanding, computationally expensive and may be more suitable for assessing truck operations of urban freight traffic, instead of regional freight traffic for strategic planning.

While the commodity-based models have more advantages than the trip-based models as they can capture more accurately the fundamental economic mechanisms of freight movements, a truck O-D trip table estimated from the commodity-based method often overlooks the non-freight truck trips (e.g., commercial truck or empty truck trips). The method presented in this chapter, therefore, aims to bridge the modeling gap of trip-based and commodity-based models by using a two-stage approach. In the next section, the proposed model framework is explained and the details on model formulation are provided.

3.3   A two-stage approach framework

Our approach divides the process into two stages: (1) develop a commodity-based truck trip table from the recent developed FAF database (FHWA, 2009), and (2) use the PFE concept to refine the truck trip table obtained from the first stage. Fig. 3.1 depicts an overall framework of this approach. The estimation is accomplished through the observed truck counts from the statewide truck count programs collected from the permanent count stations within the state and state borders.

Stage 1: Estimate Commodity-Based Truck O-D Trip Table

Stage 2: Update Truck O-D Trip Table Using Path Flow Estimator
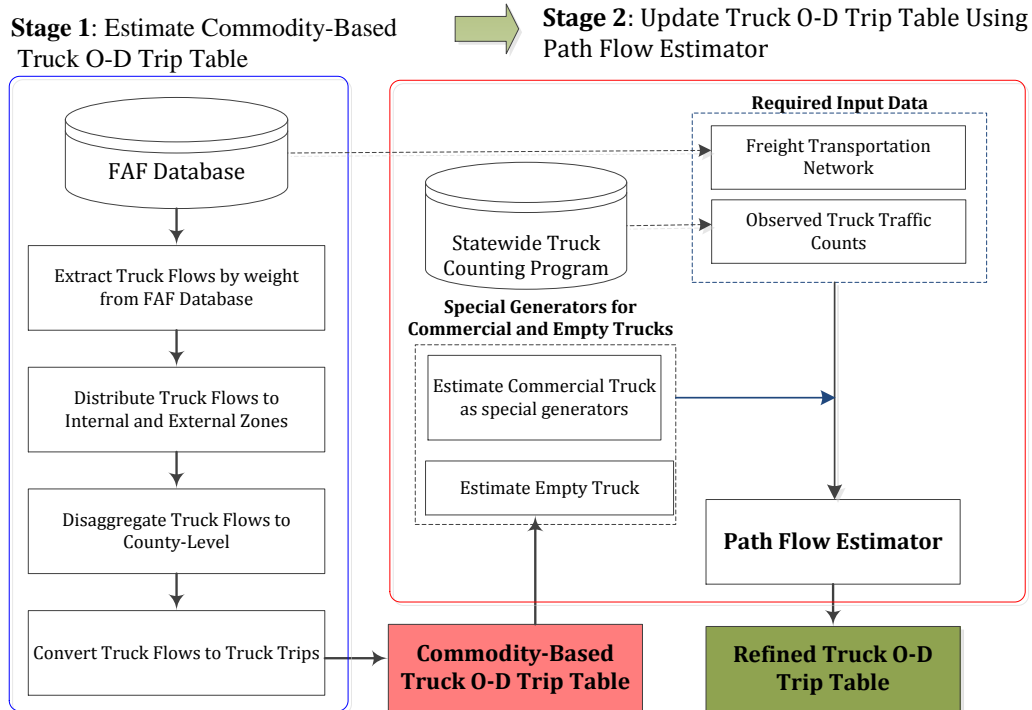
Fig. 3.1 A two-stage approach conceptual framework

The commodity-based matrix will help to guide the estimating process in the second stage as it preserves the spatial distribution of the O-D demand pattern. Details of these two stages are described in the following sections.

3.3.1 *Stage 1: develop a commodity-based truck O-D trip table*

A simplified procedure shown in Fig. 3.1 was developed in the first stage to estimate truck O-D trip table from commodity flows. This method accounts for all types of truck flows including intrastate trips (within state), interstate trips (trips originating from the state and trips destined to the state), and through trips. It includes four steps: (1) Extract truck flows by weight from FAF database, (2) Distribute truck flows to internal and external state zones, (3) Disaggregate truck flows to the county level, and (4) Convert truck flows to truck trips.

1)   Extract truck flows by weight from FAF database

The first step is to extract truck flows from the FAF commodity flow database. It should be noted that the FAF Commodity Origin-Destination Database is publicly accessible from the online database provided by Freight Management and Operations Database from the Federal Highway Administration (FHWA).The FAF commodity flow database comprises of 123 domestic (DOM) zones and 8 foreign regions for exports and imports. The DOM truck flows were extracted from the FAF database and the outputs of this step are truck flows by weight in unit of thousand tons (kTon).

2)   Distribute Truck Flows to Internal and External State Zones

This step requires quantifying four types of truck flows including: (1) truck flows within a state (Internal-Internal, I-I), (2) truck flows from a given state to other states (Internal-External, I-E), (3) truck flows from other states to a given state (External-Internal, E-I), and (4) through truck flows (External-External, E-E). It should be noted that the FAF database does not provide enough information to estimate the through truck flows (E-E). In order to estimate the through truck flows, the subarea analysis technique using the user equilibrium (UE) assignment in CUBE was used. CUBE automatically identifies the external stations that enter and exit to/from a given state. Note that the subarea analysis technique is available in other planning software packages such as TransCAD and EMME4.

3)   Disaggregate Truck Flows to the County Level

This step disaggregates the truck flows from the state level to the county level using disaggregation factors. The disaggregation factors were developed from the information of population and employment of each county. Note that the employment

and population are the most common disaggregation factors and they can be obtained from the state government organizations (e.g., Utah Governor's Office of Planning and Budget (GOPB) for population and Utah Department of Work Force Services for employment in this study (Utah Department of Workforce Services, 2008). The disaggregate factor of employment is used for truck trip production, while the disaggregate factor of population is used for truck trip attraction.

4)   Convert Truck Flows to Truck Trips

This step converts the truck flows from Step 3 to truck trips. The truck payload equivalent factor (TPEF) derived from the Federal Vehicle Inventory and User Survey (VIUS) data is employed. For Utah, the average payload for this class is 41,196 lbs/vehicle or 20.6 tons/vehicle. This number is within the reasonable range compared to the studies in other states (e.g., 16.07 tons/vehicle for Ohio (Cambridge Systematics, 2002), 24.00 tons/vehicle for Wisconsin (Wisconsin Department of Transportation,1995), 25.77 tons/vehicle for Texas (Cambridge Systematics, 2004)). After converting truck flows to truck trips, the unit is the number of truck trips per year or annual truck trips. Therefore, the annual truck trips must be converted to daily truck trips using the average number of the working days per year for trucks. According to the Highway Capacity Manual (Transportation Research Board, 2000), the average truck workdays is 300 days per year. The results of this final process are the estimated daily truck flows at the county-level.

It should be noted that estimating truck O-D trip table from the commodity flows often underestimates the local truck trips such as the light commercial and empty truck trips. Thus, in this study, we estimate the commercial trucks for each TAZ using the

commercial truck trip generation model. The commercial truck trip generation model is expressed as:

$$O_r^{comm} = \lambda^{agriculture} x_r^{agriculture} + \lambda^{basic} x_r^{basic} + \lambda^{ratail} x_r^{retail} + \lambda^{office} x_r^{office} + \lambda^{household} x_r^{household} \qquad (3.1)$$

where O_r^{comm} is the commercial truck trip production flows of origin r; $x_r^{agriculture}$, x_r^{basic}, x_r^{retail}, x_r^{office} are the employment rates for agriculture, basic (e.g., manufacturing, transportation, wholesale and utilities), retail, and office, respectively; and $x_r^{household}$ is the number of households of origin r. The calibrated coefficients ($\lambda^{agriculture}$, λ^{basic}, λ^{ratail}, λ^{office}, $\lambda^{household}$) were borrowed from the Utah Statewide Travel Model (Wilbur Smith Associates in cooperation with Resource Systems Group, 2009) (i.e., (0.166, 0.141, 0.133, 0.065, 0.038) for the urban area, and (0.050, 0.222, 0.133, 0.065, 0.038) for the rural area). The commercial truck trip attraction flows of destination s (D_s^{comm}) are assumed to be the same as the trip production flows. The empty truck trips are estimated using the HV-T model III with zero order trip chains developed by Holguín-Veras *et al.* (2010). Specifically, the empty truck trips are estimated based on the logit probability function as follows:

$$z_{sr}^{empty} = \frac{\exp(\omega_0 - \omega_1 d_{sr})}{\sum_{l \in R} \exp(\omega_0 - \omega_1 d_{sr})} z_{rs}^{loaded}, \forall r \in R \qquad (3.2)$$

where z_{sr}^{empty} are the empty truck trips between (s, r), z_{rs}^{loaded} are the loaded truck trips between (r, s), d_{sr} is the returning distance between (s, r), and ω_0 and ω_1 are coefficients empirically calibrated in the same study for large trucks (i.e., $\omega_0 =0.689$, $\omega_1 =3.452$).

Note that the logit formulation implies that the longer distance trucks (e.g., through truck traffics) would have lower probabilities of returning to their origins. The commercial truck production, attraction, and empty truck trips derived above are finally added to commodity-based production, attraction, and O-D flows.

3.3.2   *Stage 2: update truck O-D trip table using PFE*

This stage uses the optimization approach to refine the commodity-based truck O-D trip table obtained from the first stage. Hereafter, the following notation in Table 3.1 is considered. The basic idea is to use the concept of Path Flow Estimator (PFE) to estimate path flows that can reproduce the observed link counts and flows on other spatial levels. PFE is capable of estimating path flows and path travel times using only traffic counts from a subset of network links. PFE was originally developed by Bell and Shield (1995) and further enhanced by Chen *et al*. (2005). The core component of PFE is a logit-based path choice model in which the perception errors of path travel times are assumed to be independently and identically Gumbel variates. The logit model interacts with link cost functions to produce a stochastic user equilibrium (SUE) traffic pattern. It should be noted that the SUE traffic assignment procedure was also implemented to estimate the freight flows in the FAF version 3 (please refer to Chapter 5 of FAF[3] report (FHWA, 2009)). The aim of this stage is to adapt the PFE to take not only truck traffic counts but also the available freight planning data (i.e., truck production and attraction flows) to update the commodity-based truck O-D trip table. PFE requires traffic count data to estimate the statewide truck O-D trip table while the planning data is an optional input in this process.

Table 3.1: Notation for the PFE model

Notation	Description
Set of Variables	
M	: Set of network links with truck counts
U	: Set of network links without truck counts
A	: Set of all network links A=M$\cup$U
R	: Set of origins
S	: Set of destinations
RS	: Set of O-D pairs
K_{rs}	: Set of paths connecting origin r and destination s
$\bar{R}$	: Set of origins with commodity-based data
$\bar{S}$	: Set of destinations with commodity-based data
$\bar{R}\bar{S}$	: Set of target (or prior) O-D pairs
Input Variables and Parameters	
v_a	: Observed truck volume on link a
C_a	: Capacity of link a
O_r	: Commodity-based truck trip production of origin r
D_s	: Commodity-based truck trip attraction of destination s
z_{rs}	: Commodity-based O-D flows between origin r and destination s
F	: Target total demand
ε_a	: Percentage measurement error allowed for truck count on link a
ε_r	: Percentage measurement error allowed for truck trip production of origin r
ε_s	: Percentage measurement error allowed for truck trip attraction of destination s
ε_{rs}	: Percentage measurement error allowed for the commodity-based O-D demands origin r and destination s
ε	: Percentage measurement error allowed for the target total demand
θ	: Dispersion parameter in the logit model
$t_a(\cdot)$	: Truck travel time on link a
δ_{ka}^{rs}	: Path-link indicator, 1 if link a is on path k between O-D pair rs and 0 otherwise
f_k^{rs}	: Flow on path k connecting O-D pair rs
x_a	: Estimated truck traffic volume on link a
P_r	: Estimated truck trip production of origin r
A_s	: Estimated truck trip attraction of destination s
q_{rs}	: Estimated truck O-D flows between origin r and destination s
α_a, β_a	: Parameters for BPR link cost function

However, the commodity-based truck O-D trip table obtained from the first stage can enhance the observability of the O-D estimation problem as well as preserving the spatial commodity flow pattern in the study area.

Based on the equivalent mathematical programming formulation given by Fisk (1980), the PFE formulation can be formulated as a convex program with various side constraints as follows.

$$\text{Min } Z = \sum_{a \in A} \int_0^{x_a} t_a(\omega) dw + \frac{1}{\theta} \sum_{rs \in RS} \sum_{k \in K_{rs}} f_k^{rs} \ln f_k^{rs} \tag{3.3}$$

s.t.

$$(1 - \varepsilon_a) \cdot v_a \le x_a \le (1 + \varepsilon_a) \cdot v_a, \forall\, a \in M, \tag{3.4}$$

$$x_a \le C_a, \ \forall\, a \in U, \tag{3.5}$$

$$(1 - \varepsilon_{rs}) \cdot z_{rs} \le q_{rs} \le (1 + \varepsilon_{rs}) \cdot z_{rs}, \forall\, rs \in \overline{R}\overline{S}, \tag{3.6}$$

$$(1 - \varepsilon_r) \cdot O_r \le P_r \le (1 + \varepsilon_r) \cdot O_r, \forall r \in \overline{R}, \tag{3.7}$$

$$(1 - \varepsilon_s) \cdot D_s \le A_s \le (1 + \varepsilon_s) \cdot D_s, \forall s \in \overline{S}, \tag{3.8}$$

$$(1 - \varepsilon\,) \cdot F \le T \le (1 + \varepsilon\,) \cdot F, \tag{3.9}$$

$$f_k^{rs} \ge 0, \ \forall k \in K_{rs}, rs \in RS, \tag{3.10}$$

where

$$x_a = \sum_{rs \in RS} \sum_{k \in K_{rs}} f_k^{rs} \delta_{ka}^{rs}, \forall\, a \in A, \tag{3.11}$$

$$q_{rs} = \sum_{k \in K_{rs}} f_k^{rs}, \forall\, rs \in RS, \tag{3.12}$$

$$P_r = \sum_{s \in S} \sum_{k \in K_{rs}} f_k^{rs}, \forall r \in R, \tag{3.13}$$

$$A_s = \sum_{r \in R} \sum_{k \in K_{rs}} f_k^{rs}, \forall s \in S, \tag{3.14}$$

$$T = \sum_{rs \in RS} \sum_{k \in K_{rs}} f_k^{rs}, \tag{3.15}$$

The following standard BPR (Bureau of Public Road)-type link performance function is used:

$$t_a(\cdot) = t_a^0 [1 + \alpha_a (x_a / C_a)^{\beta_a}] \tag{3.16}$$

Objective function in Eq. (3.3) has two terms: an entropy term and a user equilibrium term. The entropy term seeks to spread trips onto multiple paths according to the dispersion parameter, while the user equilibrium term tends to cluster trips on the minimum cost paths. As opposed to the traditional logit-based SUE model, PFE finds path flows that minimize the SUE objective function while simultaneously reproducing truck traffic counts on all observed links in Eq. 3.4, commodity-based demands of certain O-D pairs in Eq. (3.6), truck production and attraction of certain origin and destination in Eqs. (3.7) and (3.8), and total demand in Eq. (3.9)) within some predefined error bounds. These error bounds are essentially confidence levels of the observed data at different spatial levels used to constrain the path flow estimation. A more reliable data will use a smaller error bound (or tolerance) to constrain the estimated flow within a narrower range, while a less reliable data will use a larger tolerance to allow for a larger range of the estimated flow. For the unobserved links, the estimated flows cannot exceed their respective capacities as indicated by Eq. (3.5). Eqs. (3.11)-(3.15) are definitional constraints that sum up the estimated path flows to obtain the link flows, O-D flows, zonal production flows, zonal attraction flows, and total demand, respectively. Path flows

can be derived analytically from the Lagrangian function as a function of path costs and dual variables associated with the constraints as follows.

$$f_k^{rs} = \exp\left(\theta \cdot \left(\begin{array}{c} -\sum_{a \in A} t_a(x_a)\delta_{ka}^{rs} + \sum_{a \in M}\left(u_a^- + u_a^+\right)\cdot\delta_{ka}^{rs} + \sum_{a \in U} d_a\delta_{ka}^{rs} \\ +o_{rs}^- + o_{rs}^+ + \rho_r^- + \rho_r^+ + \eta_s^- + \eta_s^+ + \psi^- + \psi^+ \end{array}\right)\right), \forall\, k \in K_{rs}, \forall rs \in RS, \quad (3.17)$$

where u_a^-, u_a^+, d_a, o_{rs}^-, o_{rs}^+, ρ_r^-, ρ_r^+, η_s^-, η_s^+, ψ^- and ψ^+ are the dual variables of constraints from Eqs. (3.4) to (3.9)), respectively. The values of u_a^+, o_{rs}^+, d_a, ρ_r^+, η_s^+, ψ^+ are restricted to be non-positive, while the values of u_a^-, o_{rs}^-, ρ_r^-, η_s^-, ψ^- must be nonnegative. For details of the derivations, please refer to Chen *et al.* (2005, 2009, 2010).

3.3.3 *Solution procedure*

The solution procedure for solving PFE consists of three main modules: (1) iterative balancing scheme, (2) column (or path) generation, and (3) output derivation from path flows. The basic idea of the iterative balancing scheme is to sequentially scale the path flows to fulfill one constraint at a time by adjusting the dual variables. Once the scheme converges, the path flows can be analytically determined. A column generation is included in the solution procedure to avoid path enumeration for a general transportation network. Finally, an output derivation procedure is used to derive information at different spatial levels using the path-flow solution from PFE (e.g., link flows, production flows, attraction flows, O-D flows, and total demand). For details of the solution procedure, please refer to Bell and Shield (1995), Chen *et al.* (2005, 2009, 2010).

3.4   Case study: Utah statewide freight transportation network

This section presents numerical results to demonstrate the features of the proposed approach as well as the applications to the Utah statewide freight transportation network. The freight transportation network of Utah was extracted from the FAF network. The network consists of 385 nodes, 944 links, and 2,256 O-D pairs. The study area consists of 29 counties and 19 external stations (i.e., entry and exit points around the state borders). The Wasatch Front Regional Council (WFRC) shown in Fig. 3.2a consists of three major counties: Salt Lake, Weber, and Davis counties. Truck traffic counts from 222 locations (about 23% of network links) were collected from the Utah Department of Transportation (UDOT) traffic map (UDOT, 2010). The observations are mainly located on the major interstate freeways of Utah, such as I-15, I-70, I-80, and I-84 (see the interstate freeways in Fig. 3.2). These major interstate freeways are the major truck routes for Utah, especially I-15 runs north-south and passing through Salt Lake City and many other cities. Note that the freight demand derived from the FAF[3] database was based on the average annual daily truck traffic (AADTT) O-D matrices, so link capacity values were required to replicate the daily equivalent capacity for a given link. To do so, we adopted the daily capacity conversion factors based on roadway classifications. The capacity was then expanded by dividing the hourly capacity by the conversion factors and used for subsequent steps.

3.4.1   Results of commodity-based truck O-D trip table

The truck O-D trip table estimation procedure described in the first stage is applied to the State of Utah for the base year (2007). A summary of the estimated commodity-based truck O-D trip table is provided here. The commodity-based daily

truck demand is 28,974 trucks/day. They are classified as follows: 52.1% are within Utah, 8.6% are from Utah to other states, 9.7% are from other states to Utah, and 29.6% are through trips. The estimated total commercial and empty truck demands derived from Eqs. (3.1) and (3.2) are approximately 60,082 trucks/day. This number indicates a high proportion of commercial and empty truck trips compared to those estimated from the commodity data only. These components are crucial for the statewide freight transportation planning model because failure to do so can result in underestimated predictions on truck demands and network congestion. Further, we use the desire lines to illustrate the commodity-based truck flows as shown in Fig. 3.2a. Note that we select only some high truck flows (i.e., greater than 500 trucks/day) to depict in the map. The circles in Fig. 3.2a represent the entering and exiting freight flows at major external stations along the interstate freeways. We can observe high entering and exiting freight flows at the external stations: between I-15 South and I-70, I-80 East and I-15 North, I-80 West, and I-80 East via I-15 near Salt Lake City and so on. They are the important interstate truck routes in Utah and are used for connecting through trips from/to other states. The O-D flows were then aggregated to show the truck trip production and attraction flows at the county level as well as the external stations shown in Fig. 3.2b. As can be seen, truck trip production and attraction flows derived from the first stage are relatively concentrated around the WFRC area compared to other counties. Fig. 3.2b shows there are more commercial and empty truck trips concentrated in the WFRC area and in Utah County (shade areas). This is expected because the major freight activities in Utah are mainly generated from these counties where warehousing and distribution centers are located.

3.4.2 Results of updated truck O-D trip table using PFE

The commodity-based O-D trip table obtained from the previous stage was input to PFE. Three different types of information: truck counts, partial set of O-D flows and production and attraction flows were used to update the truck O-D trip table. Fig. 3.3a and Fig. 3.3b depict the scatter plots of observed and estimated link flows obtained from the PFE estimation for two cases: case 1: PFE with truck counts only and case 2: PFE with truck counts and spatial constraints derived from the first stage. Accuracy of the estimates can be measured by the root mean square error (RMSE) as follows.
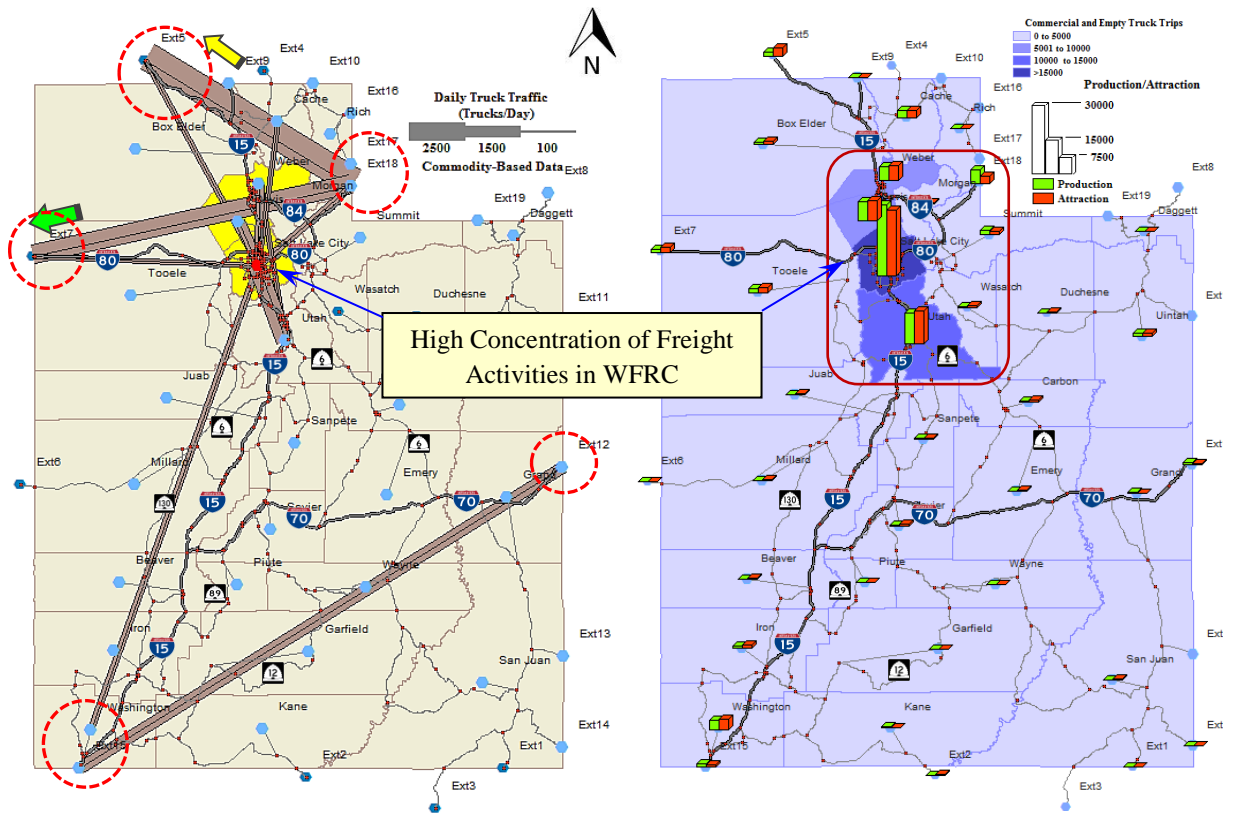
a) Commodity truck flows (desire lines)   b) Total production/attraction flows

Fig. 3.2 Estimated statewide commodity-based truck flows

$$RMSE = \sqrt{\frac{1}{N}\sum_{n=1}^{N}(x_{est}^{n} - x_{obs}^{n})^2} \, , \qquad\qquad (3.18)$$

where N is the number of observations, x_{est} and x_{obs} are the estimated and observed truck flows, respectively. The results show the truck trip table estimated by PFE produces a fairly good match for both cases (i.e., case 1: RMSE= 655.14 trucks/day, case 2: RMSE= 978.56 trucks/day). It should be noted that the RMSE indicates the aggregated quality of O-D estimates. A smaller value indicates a higher quality of the estimation process. Between the two cases, including spatial constraints into the estimation slightly deteriorates the matching of truck counts as indicated by the higher RMSE. This is compensated by the better estimates of zonal production and attraction flows. The estimated total demand of case 1 is approximately 38% less than the total demand estimated from the first stage. This highlights the importance of including the spatial constraints into the PFE model, which can better capture the total demand in case 2 (i.e., slightly over 6%). However, we still observe that case 2 underestimates some link flows, especially those links with high truck flows such as links on I-15 near Salt Lake City. This is because those links are located closed to areas with a higher level of freigth activities near the Salt Lake City International Airport. This is the concentrated area with high truck traffics accessing to/from the shipping companies and intermodal facilities such as rail-truck and air-truck modes. To resolve this issue, it requires adding special generators of truck trips from surveys of high freight density areas such as warehouses and freight distribution centers. From the modelling point of view, these special generators can be implemented in our framework as they are handled by the zonal

production and attraction constraints (in Eqs. (3.7) and (3.8)) similar to the commercial and empty truck trips.

Fig. 3.3c and Fig. 3.3d depict truck production flows for case 1 and case 2, respectively. From these two figures, we can observe the trip productions in case 2 are more distributed when the spatial constraints are considered in the estimation process. By adding zonal production and attraction flows as constraints in case 2, it can improve the observability of the trip generation pattern. Thus, this emphasizes the importance of using a two-stage approach to capture both the commodity flows and truck counts in the field, so that the statewide truck flow pattern can better reflect the reality.

3.4.3   Truck corridor analysis

This section further provides the truck corridor analysis. In Utah, I-15 is a primary corridor for both passenger and freight movements. The truck corridor serves as a backbone route for truck movements of agricultural, energy (i.e., oil, gas and coal) products in the southern Utah and onward to major cities in the state such as Provo, Salt Lake City, and Ogden. Additionaly, the I-15 corridor also helps to connect the through truck traffic as part of the CANAMEX corridor. Fig. 3.4a depicts the daily truck traffic flows on the I-15 corridor. Fig. 3.4b shows more details of the truck flow profile starting from the northern border (from Idaho) to the southen border (to Arizona).

As expected, the heavily used truck links are in the WFRC area, especially the links near Salt Lake City and its pheripheral urbanized areas such as Weber County, Davis County, and Utah County.

a) Truck count only
(Case 1)

c) Estimated trip production
(Case 1)

b) Truck count+commodity-based
data (Case 2)

d) Estimated trip production
(Case 2)
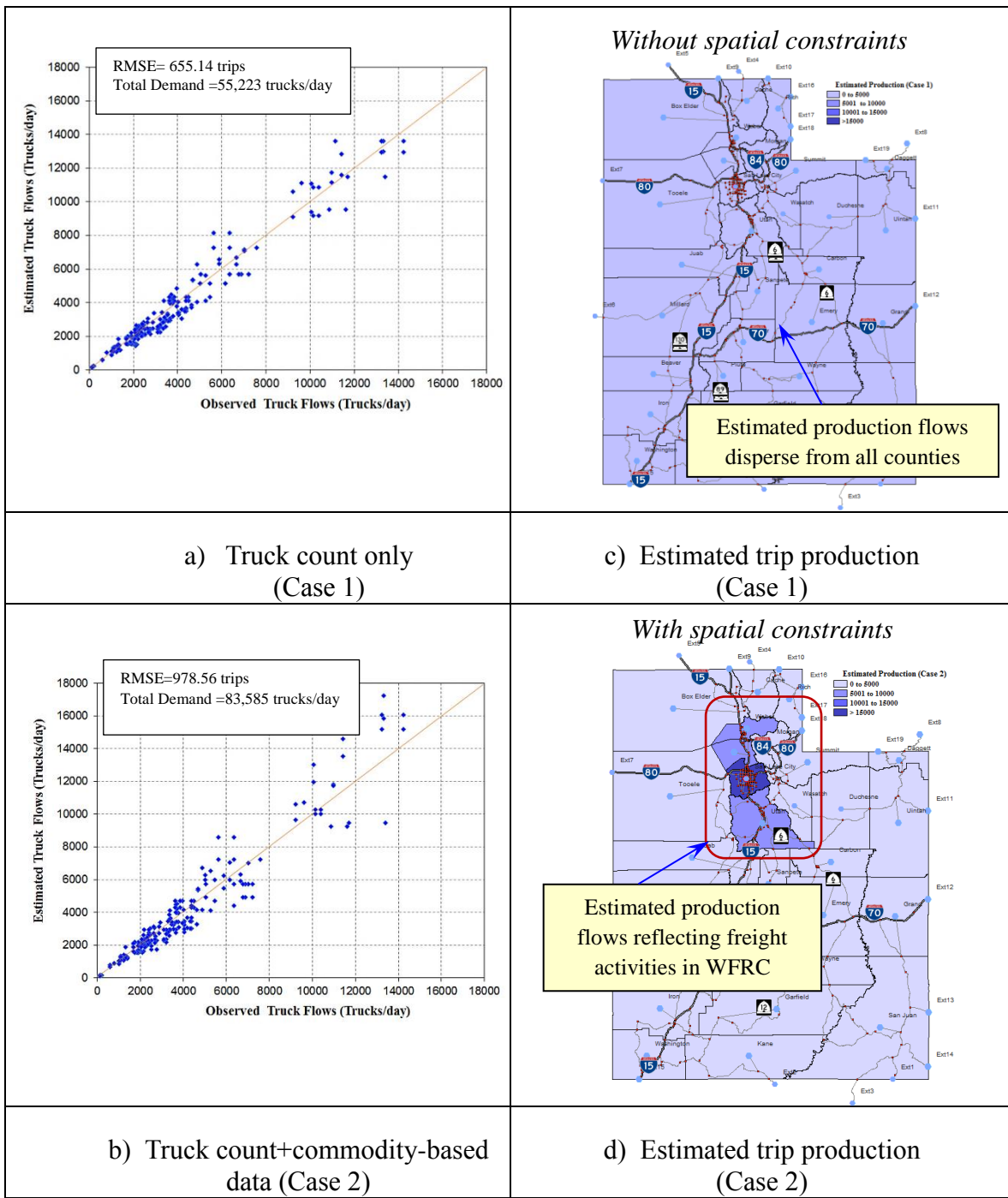
Fig. 3.3 Comparisons of observed and estimated statewide truck flows and
estimated production flows

The most congested link carries a daily truck traffic of 16,058 trucks/day with an AADT of 34,634 passenger cars/day or about 30% of this segment are truck traffics. Fig. 3.4c depicts the daily truck vehicle mile traveled (TVMT) for this corridor. Interestingly, the TVMT pattern is different from the truck flow profile pattern, specifically those in the urbanized area (i.e., area between the dotted lines). As can be seen, the TVMT of Salt Lake City is quite lower than those of Davis and Utah counties. The major reason is that higher truck flows can travel in a longer distance in those counties, while a similar amount of truck flows can travel in a shorter distance within the Salt Lake City.
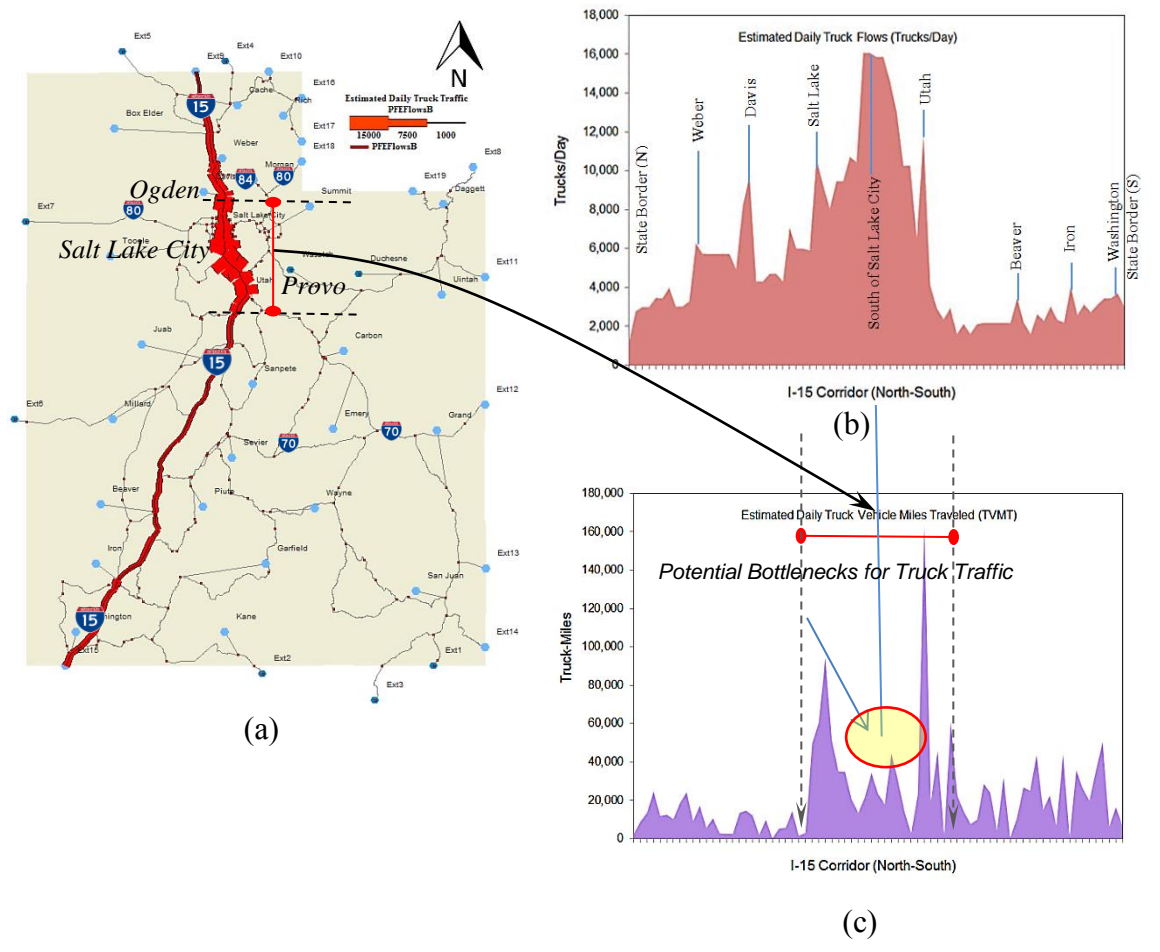
Fig. 3.4 Estimated truck flows and truck vehicle miles traveled on I-15 corridor, Utah

This suggests that these links could have higher congestion and the stop and go traffic conditions may occur around this area. A detailed bottleneck analysis can be carried out in the future to examine the issues of capacity and congestion of truck and passenger traffic flows using the truck route corridor.

3.5   Conclusions

This study has developed a two-stage approach for estimating truck O-D trip table using both commodity flows and truck counts data. The model is supported by two sequential stages: Stage one estimates the *commodity-based* truck O-D trip tables primarily derived from the commodity flow database, while stage two uses the path flow estimator (PFE) to refine the truck trip table to better match the observed truck counts. The flexibility of aggregating path flows at different spatial levels in PFE allows us to makes use of various existing field data (e.g., truck counts from the statewide truck count program collected from the permanent count locations within the state and state borders, truck VMT at the state level, etc.) and commodity-based data with commercial and empty truck trips for estimating the statewide truck trip table. The proposed approach can be also used to conduct the truck corridor analysis to determine the congested links and the potential bottlenecks. Although the results using Utah as a case study are satisfactory, accurate and consistent truck counts are required in the PFE to produce reliable results. Extending the PFE to handle inconsistent traffic counts at the statewide level should be explored (see Chen *et al.*, 2009, 2010). In addition, constraints such as trip length frequency distribution is needed to model different types of statewide truck traffics (i.e., short haul, long hual, and empty truck trips) in PFE. Substantial further work is necessary to develop the passenger traffic O-D estimation using the PFE framework so that it can

better reflect the actual congestions of the statewide transportation network. This framework has the potential to support the statewide freight planning and guide investment decisions to improve freight mobility, and thus support the statewide economic developments.

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CHAPTER 4

DEVELOPING A DECISION SUPPORT SYSTEM TOOL FOR ASSESSING

VULNERABILITY OF FREIGHT TRANSPORTATION NETWORKS

Abstract

Freight transportation networks are an essential backbone for supporting the industrial activities and economic developments of the nation. Disruption to these networks can make peoples' daily lives extremely difficult as well as seriously cripple economic productivity of the region. This paper documents the development of a decision support system (DSS) tool for assessing vulnerability of freight transportation networks. The vulnerability assessment focuses on evaluating truck-freight choke points, which are high value according to their potential economic impacts on the U.S. commerce. The vulnerability of freight chokepoints was assessed using three quantitative measures: O-D connectivity (or detour route) in terms of distance, freight flow pattern change in terms of vehicle miles traveled (VMT), and economic impact in terms of truck operating costs. The DSS tool is developed to facilitate decision making through the applications of database management capabilities, graphical user interface, GIS-based visualization, and transportation network vulnerability analysis. A *what-if* analysis approach for evaluating the consequences of network disruption scenarios is employed to demonstrate the features and applications of the DSS tool. Some strategic planning implications for preparedness and devising remedial strategies to protect the transportation network are also discussed.

4.1   Introduction

Freight transportation networks are an essential backbone for supporting the industrial activities and economic developments of national and global trade. It is a crucial component of the United States (U.S.) economy, which includes highways, railways, waterways, freight facilities and intermodal terminals. According to the latest figures from the Federal Highway Administration (FHWA, 2009), and the U.S. Census Bureau (2010, 2012), the U.S. transportation system transported a total of 17.6 billion tons of goods, valued at $18.8 trillion, in 2011 to serve almost 117 million households, and 7.4 million business establishments. The volume of goods shipped by truck and railroad are projected to increase respectively by 53% and 55% by 2040 from 2007 levels (FHWA, 2009). The steady growth in freight movements is possible because of growth in the U.S. economy, increases in the U.S. international merchandise trade, improvements in freight sector productivity, and the availability of an extensive multimodal transportation network (Bureau of Transportation Statistics (BTS), 2004). Both freight shippers and carriers generally use various modes of transportation: road, rail, water, and air (either in individually or in combination) to transport goods and raw materials for all stages of the production process in the supply chain.

Although freight transportation networks are critical to functioning of a modern society and industry, they are also fragile. Freight transportation networks are one of the *economic lifelines* which demand meticulous security consideration, especially in the aftermath of recent disastrous events such as 9/11 terrorist attacks in 2001, Hurricanes Katrina and Rita in 2005, Seattle's Hanukkah Eve Wind Storm in 2006, Minneapolis' 35W bridge collapse in 2007, Japan's Tsunami in 2011, Hurricane Sandy in 2012, and so

on. These disaster events have had adverse impact on freight transportation networks. Failures of the critical infrastructures (e.g., bridges, tunnels) on freight networks will halt or delay the transportation of goods, while disrupting industrial productivity, business continuity, and statewide economy. For instance, Hurricane Sandy in winter of 2012 overwhelmed the roadways and disrupted freight movements across the state of New York and many areas in the East Coast. The IHS Global Insight (2012) estimated the total economic losses based on the disruptions to infrastructure and business activity to be between $30 billion to $50 billion, or up to 0.6% points off the annualized fourth-quarter real GDP growth.

Due to the complexity of the problem, the development of a decision support system (DSS) tool that provides quantitative analysis for analyzing network disruptions and evaluating potential response measures is needed. The DSS tool is necessary for the decision makers (DMs) to characterize network vulnerability and help them to understand the consequence of network disruption. Government agencies need to identify their preparedness for all types of emergency situations and are required to examine their preparedness and abilities to respond and recover from such events in a timely manner (Thompson *et al*., 2006; Yoon *et al*., 2008). However, the national-developed decision support systems such as the Disruption Impact Estimation Tool-Transportation (DIETT) by the Transportation Research Board (2006) for identifying and prioritizing bridges based on transportation and economic impacts, and the Hazards U.S.-Multi-Hazard (HAZUS-MH) by the Federal Emergency Management Agency (FEMA, 2011) for estimating damage and losses of buildings and facilities resulting from natural disasters have limited ability to capture the interplay between *freight flows* (i.e., transportation

demand) and *transportation networks* (i.e., transportation supply) which are the crucial factors for analyzing the vulnerability of freight transportation networks.

The primary objective of this research effort is to develop a DSS tool for assessing the vulnerability of freight transportation networks. The vulnerability assessment focuses on evaluating truck-freight chokepoints, which are high value according to their potential economic impact on the U.S. commerce. To demonstrate the applications of DSS, this study conducts a case study based on the disruption scenarios of highway bridges on the highway system in the state of Utah. The organization of this paper is as follows. Section 4.2 gives an overview of the DSS tool including its architecture and input data required for the vulnerability assessment analysis. In this section, we describe a simplified procedure for estimating the truck origin-destination (O-D) trip table, which is used as the major input for the assessment process. Section 4.3 explains the methods used for vulnerability assessment and implementation and workflows of the DSS tool. In Section 4.4, we demonstrate the applicability of the DSS tool via a case study using the Utah freight transportation network. Results of the vulnerability assessment in terms of O-D connectivity, freight flow pattern change, and economic impact are summarized in this section. Section 4.5 provides some concluding remarks and future research directions.

4.2   An overview of a DSS

This section describes the DSS architecture designed to facilitate three major components including data inputs, assessment model, and data outputs. They are briefly explained as follows.

4.2.1 *Architecture of a DSS*

The DSS architecture is illustrated in Fig.4.1. The proposed system consists of three fundamental components including: (1) data inputs, (2) vulnerability assessment model and GIS tool, and (3) outputs. Three fundamental data inputs required for the vulnerability assessment analysis include freight transportation network, truck O-D trip table, and chokepoint locations. The vulnerability assessment analysis is developed based on three submodels including (1) *O-D Connectivity Analysis*, (2) *Freight Flow Pattern Change Analysis*, and (3) *Economic Impact Analysis*.

The DSS tool was implemented as a stand-alone GIS application. The core GIS component is an ActiveX control, MapWinGIS.ocx programmed in MS Visual Basic.NET. MapWindow is a mapping tool, a GIS modeling system, and a GIS application programming interface (API) with redistributable open source form and free source code access (Ames, 2012). Because of the open source environment, the graphical user interface (GUI) in the DSS tool is customized to include built-in tools called *Assessment Panel* that allows user to create the scenarios, run the analysis, and save and compare results in tabular and GIS formats. Details of inputs required for the DSS tool are described in the following subsections.

4.2.2 Freight transportation network

The freight transportation network in our study is extracted from the Freight Analysis Framework (FAF) commodity flow database developed by the Office of Freight Management and Operations under FHWA (2007b).
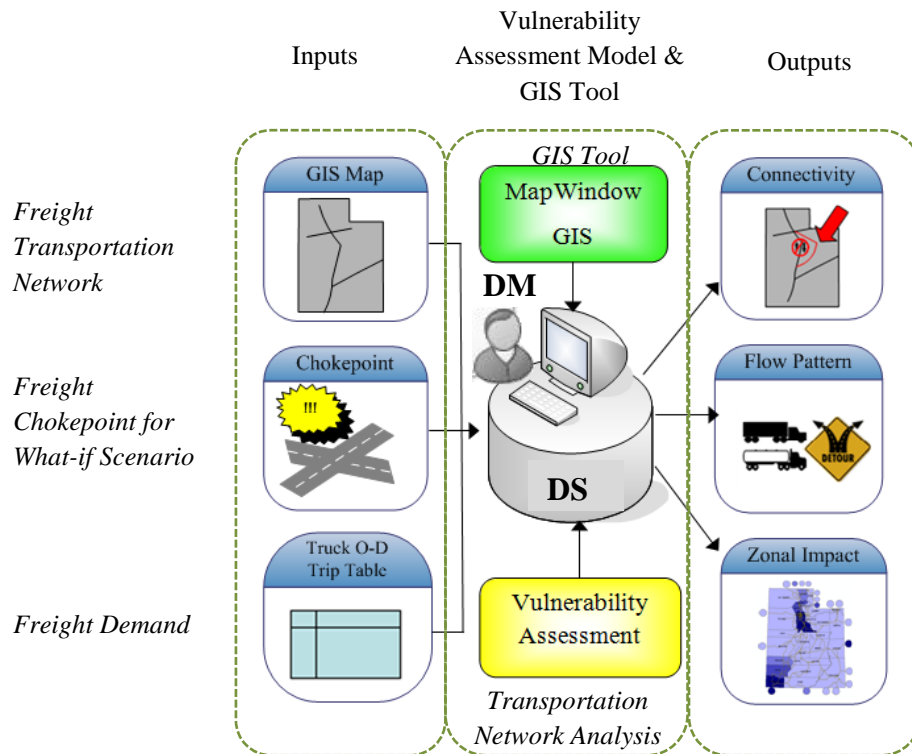
Fig.4.1 Architecture of a DSS

The Utah freight transportation network consists of 908 links, 817 nodes, and 48 traffic analysis zones (i.e., 29 internal zones representing the counties in Utah and 19 external stations representing the zones at the state's borders). The network attributes including network connectivity, link length, link type (i.e., one-way or two-way), and total and directional demand are necessary for the vulnerability assessment analysis. The analysts can enable or disable the potential freight chokepoints in the scenario analysis, so an additional binary integer attribute is added to the link database representing its operational state (i.e., 0 represents that the link is completely impassible due to network disruption and 1 otherwise).

4.2.3   Freight chokepoints

Cambridge Systematics (2005) classified *freight chokepoint*, or alternatively called *freight bottleneck*, using a combination of three features including (1) type of constraint (i.e., capacity constraint), (2) type of roadway (e.g., interstate highway or arterial), and (3) type of freight route (e.g., truck route or truck corridor). In their assessments, freight chokepoints can be identified based on the physical locations on highways that routinely experience recurring congestion and traffic backups because traffic volumes exceed highway capacity. Likewise, the Washington Department of Transportation (WSDOT, 2005) defined chokepoint as the place where delay occurs because of traffic interference and/or the roadway configuration (e.g., freeway interchanges; lack of left-turn lanes at intersections; seasonal road closures, bridges), while bottleneck is the place where roadways are physically narrow, causing congestion. Witte *et al*. (2012) gave some examples of bottleneck in the European freight transportation network. They defined bottleneck as places with congestion-involved, capacity constraint, and other issues beside capacity constraints such as accident or hazard. The Wasatch Front Regional Council (2008) in Utah defined chokepoints as the critical narrow locations that have difficulty to pass through (e.g., bridges, tunnels). There are generally few alternatives for moving around these locations and hence are susceptible to incidents and disruptions. In our study, freight chokepoints are selected from the structurally deficient bridges on the Utah highway network, and used in the *what-if* analysis. Details of these chokepoint locations are described in Section 4.4.

4.2.4   Freight demand

In this study, we developed a simplified procedure for estimating truck O-D trip table from the FAF database (Office of Freight Management and Operations, FHWA, 2007b) to be used as the truck freight demand for the vulnerability assessment analysis. Fig. 4.2 graphically depicts the procedure of a simplified method to estimate truck O-D trip table. Note that the FAF commodity database can be publicly accessed from the Freight Management and Operations Database website.[2] It consists of three major databases: (1) DOM database: the commodity flows between domestic origins and domestic destinations, (2) BRD database: the commodity flows by land from Canada and Mexico to domestic destinations via ports of entry on the U.S. border and vice versa, and (3) SEA database: the commodity flows by water from overseas origins via ports of entry to domestic destinations and vice versa. The measurement units of the commodity flow database are in units of thousand of tons (KT) and million of dollars (MDOL). To extract the truck O-D demand for our study area (i.e., state of Utah) from the DOM database, a pre-processing technique called *Subarea Analysis* was implemented in TransCAD, a transportation planning software by Caliper Cooperation. This step aggregates the 114 FAF zones to 49 state zones. It requires quantifying four types of truck flows including: (1) truck flows within Utah (Internal-Internal, I-I), (2) truck flows from Utah to other states (Internal-External, I-E) or production flows, (3) truck flows from other states to Utah (External-Internal, E-I) or attraction flows, and (4) through truck flows (E-E).

The next step is to disaggregate the truck flows from the state level to the county level using population and employment rates as the disaggregation factors.

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[2] Available at: http://ops.fhwa.dot.gov/freight/freight_analysis/faf/index.htm
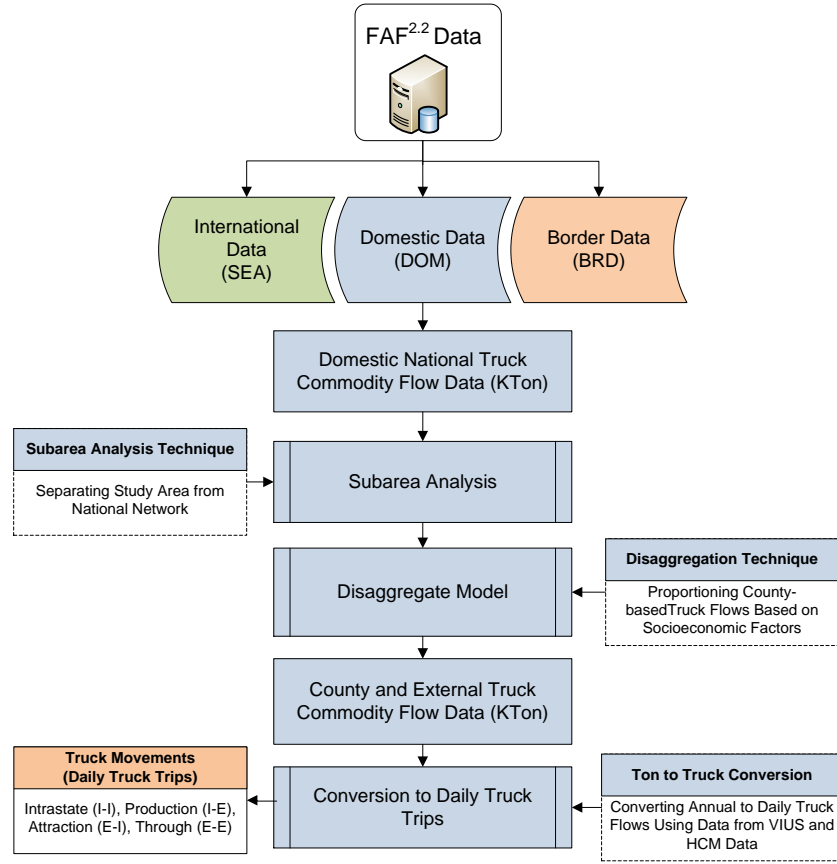
Fig. 4.2 Commodity-based truck O-D trip table estimation process

These factors are calculated according to Equations (1) and (2) as follows.

$$O_c = \frac{Emp_c}{\sum\limits_{c=1}^{C} Emp_c} \tag{4.1}$$

$$D_c = \frac{Pop_c}{\sum\limits_{c=1}^{C} Pop_c} \tag{4.2}$$

where O_c is the disaggregation factor of truck production flows for county c; D_c is the

disaggregation factor of truck attraction flows for county c; Emp_c is the employment rate

of county *c*; Pop_c is the population rate of county *c*, and *C* is the number of counties in Utah. The last step is to convert truck flows to truck trips using the truck payload equivalent factor (TPEF). Note that TPEF can be simply analyzed from the Federal Vehicle Inventory and User Survey (VIUS) data (Office of Freight Management and Operations, FHWA, 2007a). The result indicates that TPEF is 41,196 lbs/vehicle or 20.6 tons/vehicle. This number is in a reasonable range compared to the empirical studies in other states (e.g., 16.07 tons/vehicle for Ohio (Cambridge Systematics, 2002), 24.00 tons/vehicle for Wisconsin (Wisconsin Department of Transportation, 1995), and 25.77 tons/vehicle for Texas (Cambridge Systematics, 2004). In the final step, we adopted the number of working days per year for truck operations from the Highway Capacity Manual (HCM) (Transportation Research Board, 2000) (i.e., 300 workdays per year) to convert the annual truck flows to daily truck flows.

4.3   Development of a DSS

4.3.1   *The vulnerability assessment method*

The vulnerability of freight chokepoints are assessed using three quantitative measures: (1) O-D connectivity, (2) freight flow pattern change, and (3) zonal and network economic impacts. Details of these measures are described as follows.

4.3.1.1 O-D connectivity

Because the shortest routes between O-D pairs could be impassible during network disruption, the alternate or "second-best" routes are important for rerouting truck traffic. The network connectivity of all O-D pairs is re-assessed using the shortest path algorithm by Dijkstra (1959). This algorithm is an iterative application of the one-to-one

(or the one-to-many) shortest path problem. All links *(i, j)* in the network are assumed to have non-negative distances *l(i, j)*. The algorithm begins at a specified source node *r* and successively finds the closest, second closest, and so on, node to the source node, until a specified terminal node is reached (or until the shortest paths to all network nodes are found). As such, the algorithm is a simple *label setting* method. In the evolution of the algorithm, each node can be labeled as in one of two states: (1) Open State: when the node still has a *temporary label* and (2) Closed State: when the node is assigned a *permanent label*. Note that the following vectors are used to store path lengths and predecessor nodes:

1. *d(j)*= length of current shortest path from node *r* to node *j*

2. *p(j)* = immediate *predecessor node* to *j* in the current shortest path

The algorithm can be described step by step as follows:

Step 0: Initialization. Set *d(r)=0, p(r)=**, node *r* is *closed* (permanently labeled).

Set *d(j)=∞, p(j)=0*, all nodes *j* are *open*. Set last node closed label *k=r*.

Step 1: Update labels. Examine all links *(k, j)* outbound from last closed node. If node *j* is closed, go to next link; if node *j* is open, set length label to:

$$d(j)= \text{Min} [\ d(j), \ d(k)+l(k, j) \ ]$$

Step 2: Choose node to close. Compare *d(j)* for all open nodes; choose the node with the minimum *d(j)* as the next node to close (add to shortest path tree), call node *i*.

Step 3: Find predecessor node. Consider the links *(j, i)* leading from *closed* nodes to *i* until one is found that satisfies:

$$d(i) - l(j, i) = d(j)$$

Call this predecessor node *q* and set *p(i)=q*. Node *i* is closed.

Step 4: Stopping rule.

(a) For one-to-all nodes shortest paths, if all nodes are closed, then *stop*.

(b) For a one-to-one node shortest path, if destination node is closed, then *stop*.

Otherwise, set $k=i$, and return to Step 2.

It should be noted that the algorithm has been modified to address the situation when a node or subset of nodes are unreachable from all other nodes. In this case, the list of these unreachable nodes is reported to the users as very high distances. The detour distance between an O-D pair after the chokepoint disruption can be simply computed as follows.

$$\Delta d_{rs}(g) = d_{rs}\big(G(N, L-g)\big) - d_{rs}\big(G(N,L)\big) \tag{4.3}$$

where N is the number of nodes in the network G, L is the number of links in the network G, $d_{rs}\big(G(N, L)\big)$ is the distance on the shortest path between origin r and destination s for all O-D pairs under the complete network $G(N,L)$ without disruption, g is a chokepoint link under disruption, L-g is the resulting network after chokepoint g is removed from the network $G(N, L-g)$, $d_{rs}\big(G(N, L-g)\big)$ is a shortest path distance between origin r and destination s for all O-D pairs under the disrupted network $G(N, L-g)$, and $\Delta d_{rs}(g)$ is the difference between the shortest path after g is removed from the network and the shortest path with the network intact, or the additional cost in terms of distance on the detour route when the best route is not available after g is removed from the network.

4.3.1.2 *Freight flow pattern change*

To assess the freight flow pattern change, a traffic assignment procedure is used to assign truck O-D flows onto the freight transportation network. In this study, the all-or-nothing (AON) traffic assignment method is adopted. The AON method assumes that flows are assigned based on the fixed travel cost (distance) and does not vary with

congestion. To measure the impact of the freight flow pattern, the vehicle miles traveled (VMT) measure, computed from the truck flows and distance between each O-D pair, is also used to measure the impact. The VMT of truck flows between O-D pair *r-s* is computed as follows:

$$VMT_{rs}(G(N,L)) = d_{rs}(G(N, L)) \times f_{rs} \tag{4.4}$$

where $d_{rs}(G(N, L))$ is the distance on the shortest path between O-D pair (r, s) under network *G(N,L)*, and f_{rs} is the annual average daily truck flow (unit: truck/day) between O-D pair (r, s) obtained from the truck O-D trip table in Section 4.2.4. The impact of freight flow pattern change can then be computed based on the increased VMT when one or more chokepoints *g* are removed from the network, that is:

$$\Delta VMT_{rs}(g) = VMT_{rs}(G(N,L-g)) - VMT_{rs}(G(N,L)) \tag{4.5}$$

$$= f_{rs}[d_{rs}(G(N,L-g)) - d_{rs}(G(N,L))] = f_{rs}[\Delta d_{rs}(g)] \tag{4.6}$$

4.3.1.3 *O-D, zonal, and network economic impacts*

The economic impacts are also measured as an increased VMT at the zonal level by origin, zonal level by destination, and network level for different planning evaluation purposes. Note that a higher increased VMT corresponds to traveling longer distances due to detour when encountering one or more link failures on the primary best route. Additionally, we convert the transportation network impact to the economic impact using the operating cost factors studied by the American Transportation Research Institute (ATRI, 2008). Based on the results of that analysis, it was determined that it costs $1.73 for a truck to move one mile on average, and if traveling for one hour, the operating cost

is \$83.68. Details of the motorized carrier costs are summarized in Table 4.1. We use γ to denote the truck operational cost per mile. The economic impacts at O-D level (Z_{rs}), origin level (Z_r), destination level (Z_s) and network level (Z_{net}) can be computed as follows.

♦ O-D level
$$Z_{rs}(g) = \gamma f_{rs}[\Delta d_{rs}(g)], \quad \forall rs \in RS, \tag{4.7}$$

♦ Zonal level by Origin
$$Z_r(g) = \gamma \sum_{s \neq r}^{S} f_{rs}[\Delta d_{rs}(g)], \quad \forall r \in R, \tag{4.8}$$

♦ Zonal level by Destination
$$Z_s(g) = \gamma \sum_{r \neq s}^{R} f_{rs}[\Delta d_{rs}(g)], \quad \forall s \in S, \tag{4.9}$$

♦ Network (or area) level
$$Z_{net}(g) = \gamma \sum_{r \neq s}^{R} \sum_{s}^{S} f_{rs}[\Delta d_{rs}(g)]. \tag{4.10}$$

Table 4.1: Motorized carrier costs

Motorized Carrier Marginal Expense	Costs Per Mile (USD)	Costs Per Hour (USD)
Vehicle-based		
Fuel-Oil Costs	0.634	33.00
Truck/Trailer Lease or Purchase Payments	0.206	10.72
Repair and Maintenance	0.092	4.79
Fuel Taxes	0.062	3.23
Truck Insurance Premiums	0.06	3.12
Tires	0.03	1.56
Licensing and Overweight-Oversize Permits	0.024	1.25
Tolls	0.019	0.99
Driver-based		
Driver Pay	0.441	16.59
Driver Benefits	0.126	6.56
Driver Bonus Payments	0.036	1.87
Total Marginal Costs	1.73	83.68

Source: ATRI, 2008

4.3.2   Implementation and workflows

The DSS tool consists of three main modules including scenario generation, vulnerability assessment, and economic impact assessment. Fig. 4.3 shows the work flow process of the DSS tool. The graphical user interfaces (GUIs) are developed to facilitate the user's inputs and outputs at each step.

At the first step, the DSS tool reads the shapefile data including freight transportation network (i.e., node/link), its connectivity, link attributes (i.e., length, speed limit, etc.), demand file, and transportation-related risk map (e.g., seismic map) by overlaying the various layers of GIS maps. User can then select the freight chokepoints from the Network Editor Tool (NET) to create the disruption scenarios for the case study. After network data are processed, user can run the assessment model to output connectivity, freight flow pattern change, and zonal impacts, respectively.

At this step, user can query and visualize the O-D connectivity with four options: (1) one origin to one destination, (2) one origin to all destinations, (3) all origins to one destination, and (4) all origins to all destinations. These connectivity and freight flow pattern results are stored and later used for comparing different scenarios. The GIS map results can be stored in the Extensible Markup Language (XML) format, which can be edited directly from the XML editor, and can be shared across different database management systems (e.g., MS Access, Oracle, and SQL). The graphical user interface (GUI) and its components including menu bar, map preview, map legend, toolbar buttons, and assessment panel are illustrated in Fig. 4.3.
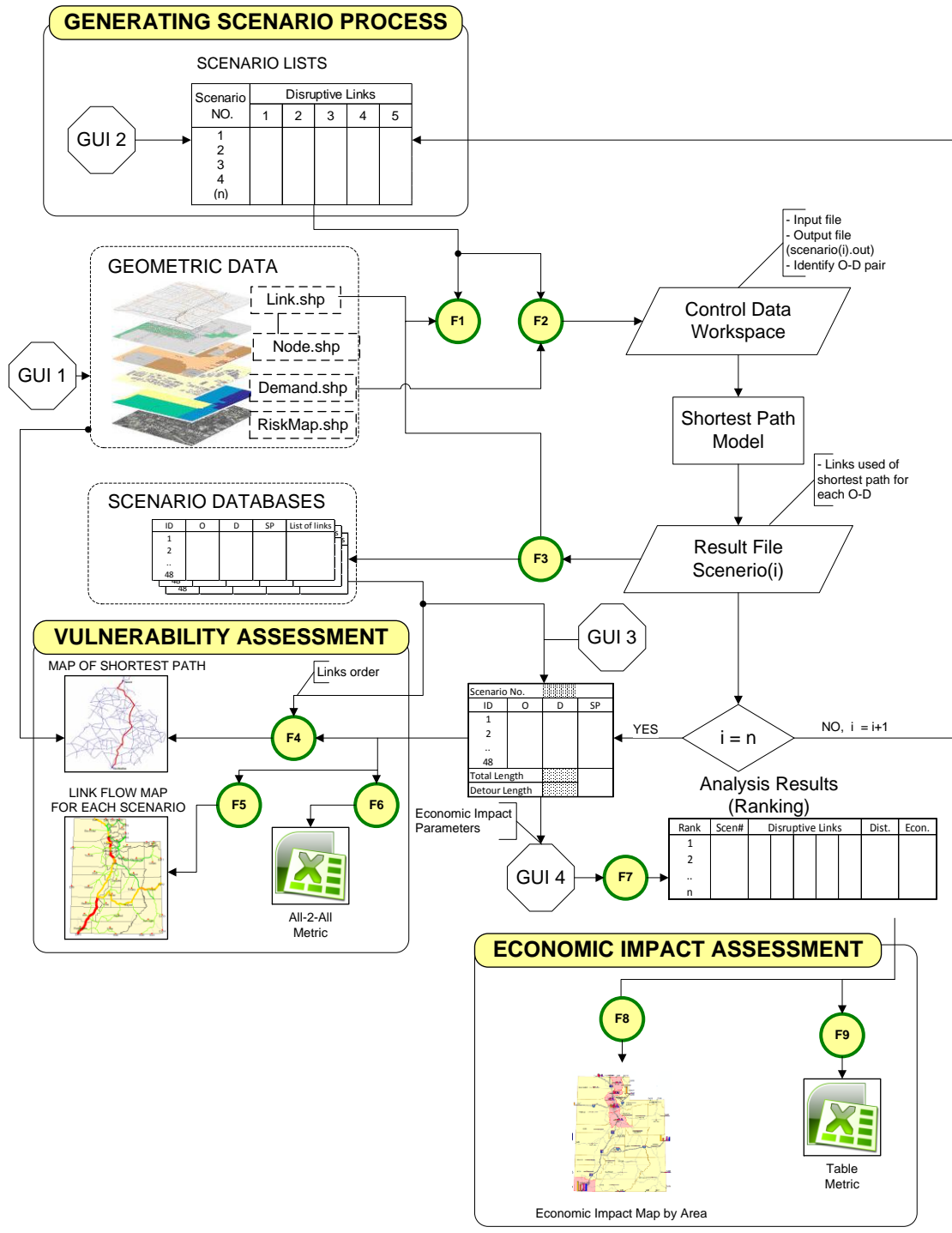
Fig. 4.3 Workflow process of the DSS tool
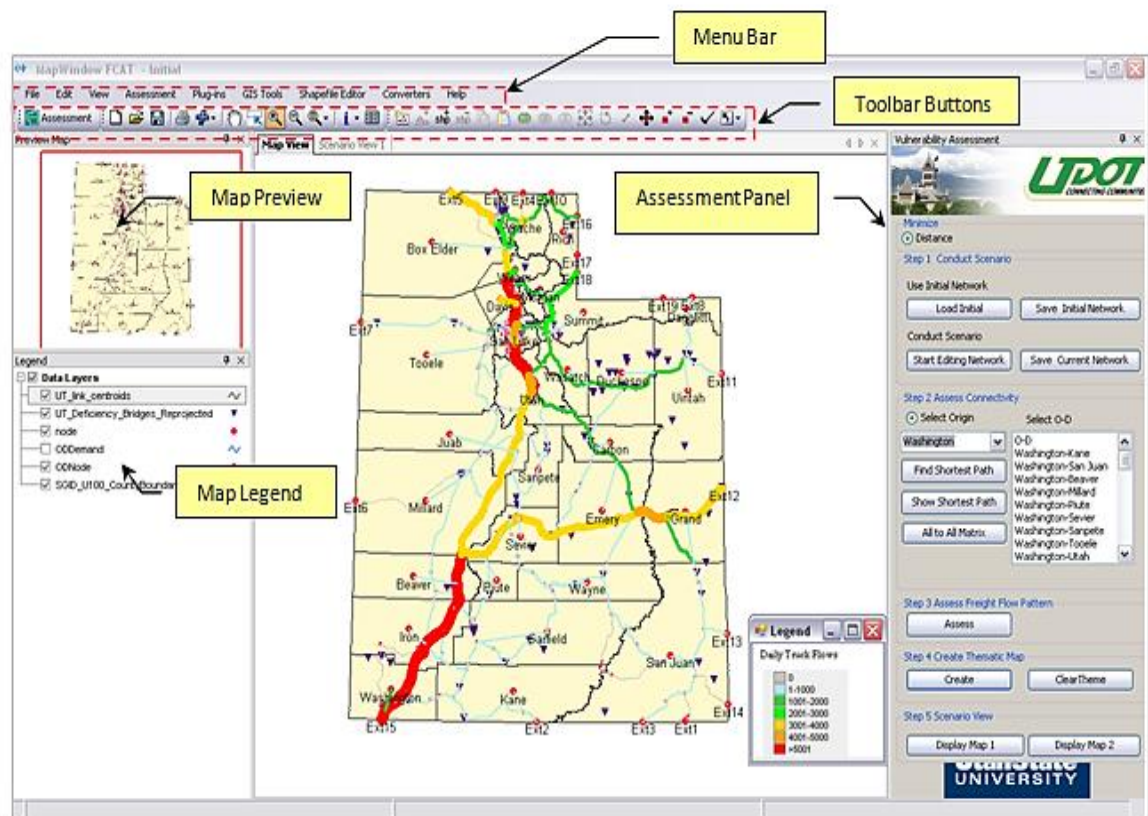
Fig. 4.4 The GUI of a DSS and its components

4.4   Case study and results

4.4.1   Scenario generation

The case study adopts a "*what-if*" analysis approach to generate freight chokepoint disruption scenarios. To generate such scenarios, the structurally deficient bridges from the National Bridge Inventory (NBI) (Office of Engineering Bridge Division, USDOT, 2004) database are used. The NBI uses the condition rating, varying from 0 to 9, to describe the existing in-place bridge compared to the as-built condition. The NBI condition rating is determined from the physical condition of four components including (1) super structure, (2) deck, (3) substructure, and (4) culvert. Fig. 4.5 provides an

illustration of these four components. According to the FHWA definition, a structurally deficient bridge refers to a bridge which has a condition rating less than or equal to 4 for at least one of these four major components. Using the 2002 NBI database, there are about 221 out of 2,854 bridges classified as structurally deficient bridges in Utah. The structurally deficient bridges are further classified by the highway functional class and area type. For the interstate highway, there are about 27 bridges in the rural area and 32 bridges in the urban area that are considered to be structurally deficient.

To conduct the case study due to bridge failures in an earthquake, the seismic hazard map developed by Halling *et al*. (2002) was used. Fig. 4.5a depicts a GIS map of the seismic hazard superimposed with the locations of structurally deficient bridges in Utah. The seismic hazard map for Utah was developed based on the deterministic maximum peak bedrock acceleration determined by the length of fault ruptures and slip type expected in an earthquake.

The acceleration is measured in terms of the deterministic peak ground acceleration (PGA), which indicates how hard the earth shakes in a given geographical area. The contour lines show the various levels of PGA intensity. As can be seen, many of the structurally deficient bridges (denoted with the red dots) are in the high PGA intensity areas which indicate that these bridges are highly vulnerable to an earthquake. Using the intersection function in MapWindow GIS to intersect between structurally deficient bridges and the PGA intensity polygons, we can obtain the critical bridges that are located in the high seismic risk areas. Fig. 4.6a shows the locations of vulnerable bridges in the case study.

Deck (2)

Superstructure (1)

Substructure (3)

Culvert (4)

(1)　　　　　　(2)　　　　　　(3)　　　　　　(4)
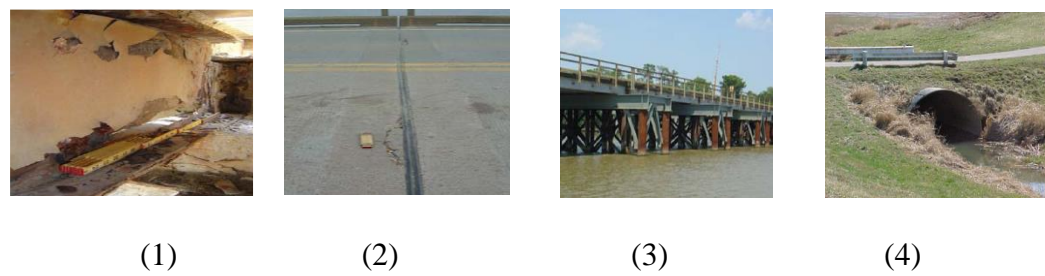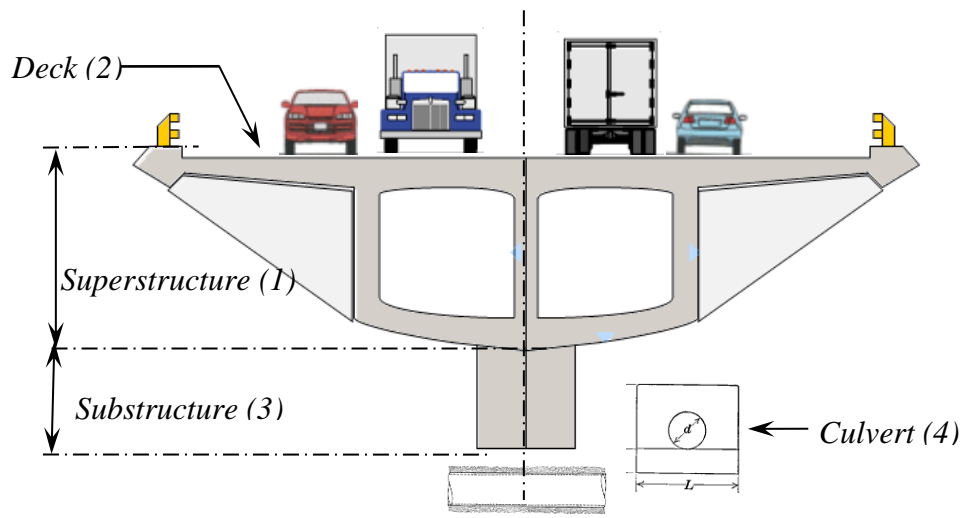
Image Source: Structure and Bridge Division, Virginia Department of Transportation

Fig. 4.5 Structurally deficient components: (1) super structure, (2) deck,
(3) substructure, and (4) culvert

In Fig. 4.6b, eight disruption scenarios are conducted: one for each of the five selected rural (scenario A, B, C) and urban interstate bridges (scenario D, E), specifically in the metropolitan region of Utah, one for the three rural bridges combined (scenario F), one for the two urban bridges combined (scenario G), and one for all five bridges combined (scenario H).

The case study assumes that the disrupted bridges result in service shut down and we consider two groups of bridges in rural and urban areas. Rural interstate bridges are

important for interstate and interregional freight. The following three scenarios are considered for vulnerability assessment using the rural interstate bridges:

- Scenario A: Bridge at Eagle Canyon, Rural Interstate 70
- Scenario B: Bridge at Silver Creek, Rural Interstate 80
- Scenario C: Bridge near Beaver County, Rural Interstate 15

These three structurally deficient bridges are located in the relatively high seismic hazard area, and they are critical for interstate (or long-haul truck) freight transportation. On the other hand, urban bridges are vital for moving people and goods in the metropolitan area due to high traffic volumes. Disruptions to these bridges could have an adverse impact on the population living in the urban areas. In the urban interstate bridge case, the following two scenarios are considered for vulnerability assessment:

- Scenario D: Bridge at Roy (5600 South), Weber County, Urban Interstate 15
- Scenario E: Bridge at Salt Lake City (Near 2300 N. and Beck St.), Salt Lake County Urban Interstate 15

In addition to the above single bridge failure scenarios (both rural and urban), the following multiple bridge failure scenarios are considered:

- Scenario F: Disruption of Scenarios A+B+C (Rural Interstate Bridges)
- Scenario G: Disruption of Scenarios D+E (Urban Interstate Bridges)
- Scenario H: Disruption of Scenarios A+B+C+D+E (Both Rural and Urban Interstate Bridges)

(a)   (b)
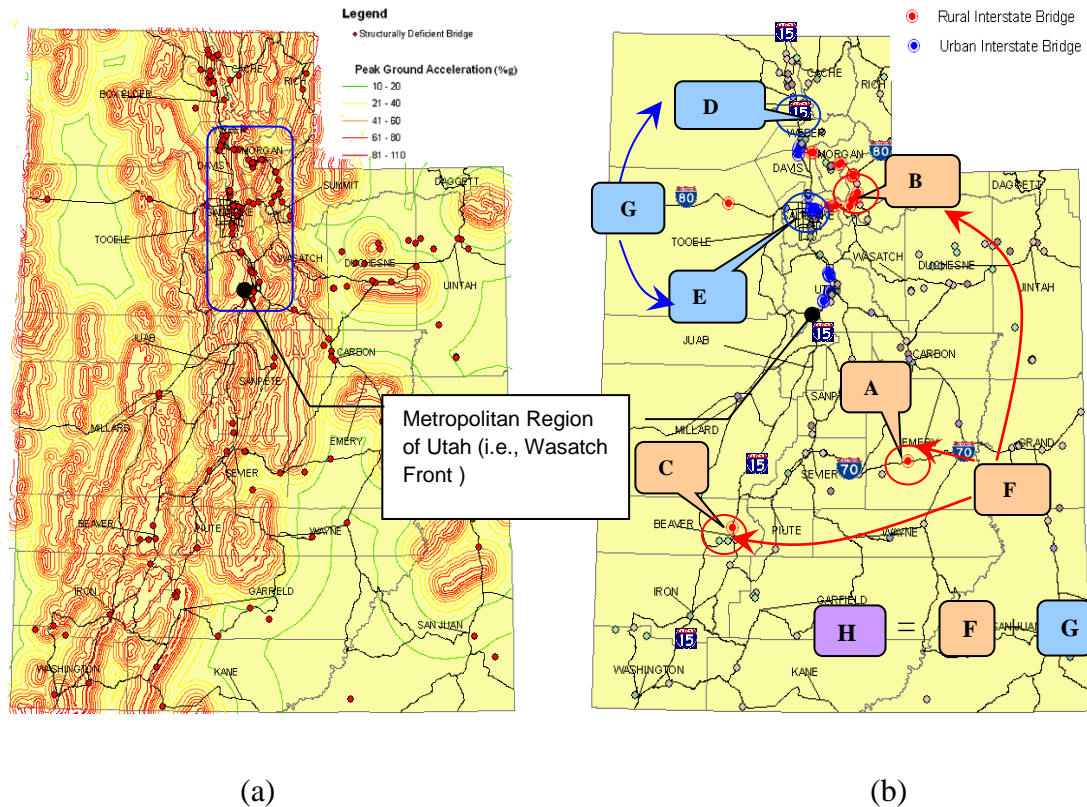
Fig. 4.6 a) Deterministic maximum peak bedrock acceleration map and locations of the structurally deficient bridges in Utah, b) locations of the disrupted bridges in scenarios

Though the multiple bridge failure scenarios are rare (i.e., low likelihood), the results of these scenarios are useful as they provide guidelines for DMs and their working groups to establish a multi-jurisdictional and multi-stakeholder collaboration and response.

4.4.2 Results and analysis

The spatial outputs of the what-if scenarios can be visualized in the GIS map. For each scenario, the O-D connectivity, freight flow pattern change, and economic impacts from all origins to all destinations are summarized in a tabular format. We use a color-coded technique to indicate the severity level (i.e., the range of the severity level is defined by the

analyst: high, medium, and low). For the network, user can query/manage/export the assigned link flows (in unit of daily truck trips) using NET. With this feature, the DMs can visually identify the O-D pairs that are adversely affected by bridge failure(s) and the magnitude of truck traffic in the detour routes. For instance, Fig. 4.7 depicts the results of Scenario A.

As can be seen, the disrupted bridge in Scenario A is located in the rural area where there are limited alternate routes or adjacent streets nearby. The O-D pair that has been affected by the disruption is between Sevier county and External Station 12 at Interstate 70 East (I-70E) near the border of Utah. The detour distance for this O-D pair is approximately 60 miles through the state routes as shown in Fig. 4.7a. In addition, the VMT increases, particularly for the top three affected O-D pairs (i.e., External Station 15 at I-15 South to and from External Station 12 at I-70 East, and Washington County to External Station 13 near the border of Utah and Colorado) as shown in Fig. 4.7b.

In brief, the total travel distances and VMTs of Scenario B and Scenario C also increase, but they are smaller than those shown in Scenario A. Additionally, Scenario D and Scenario E (in the urban area) has less impacts in both connectivity and freight flow pattern change compared to those of the scenarios in the rural areas. This is because there are more alternative routes (i.e., arterial roads) in the urban areas, so truck drivers can use them to avoid the closures.

Fig. 4.8a and Fig. 4.8b show the aggregated zonal impacts (i.e., zonal impacts by origin) of multiple rural and urban bridges in Scenarios F and G. The results show that the disruption of bridges in rural areas (Fig. 4.8a) has more adverse impacts than those in the urban areas.

*Color-coded Table for O-D Connectivity (User defined Impact: Red=High, Yellow=
Medium, Green=Low)*

(a)   (b)
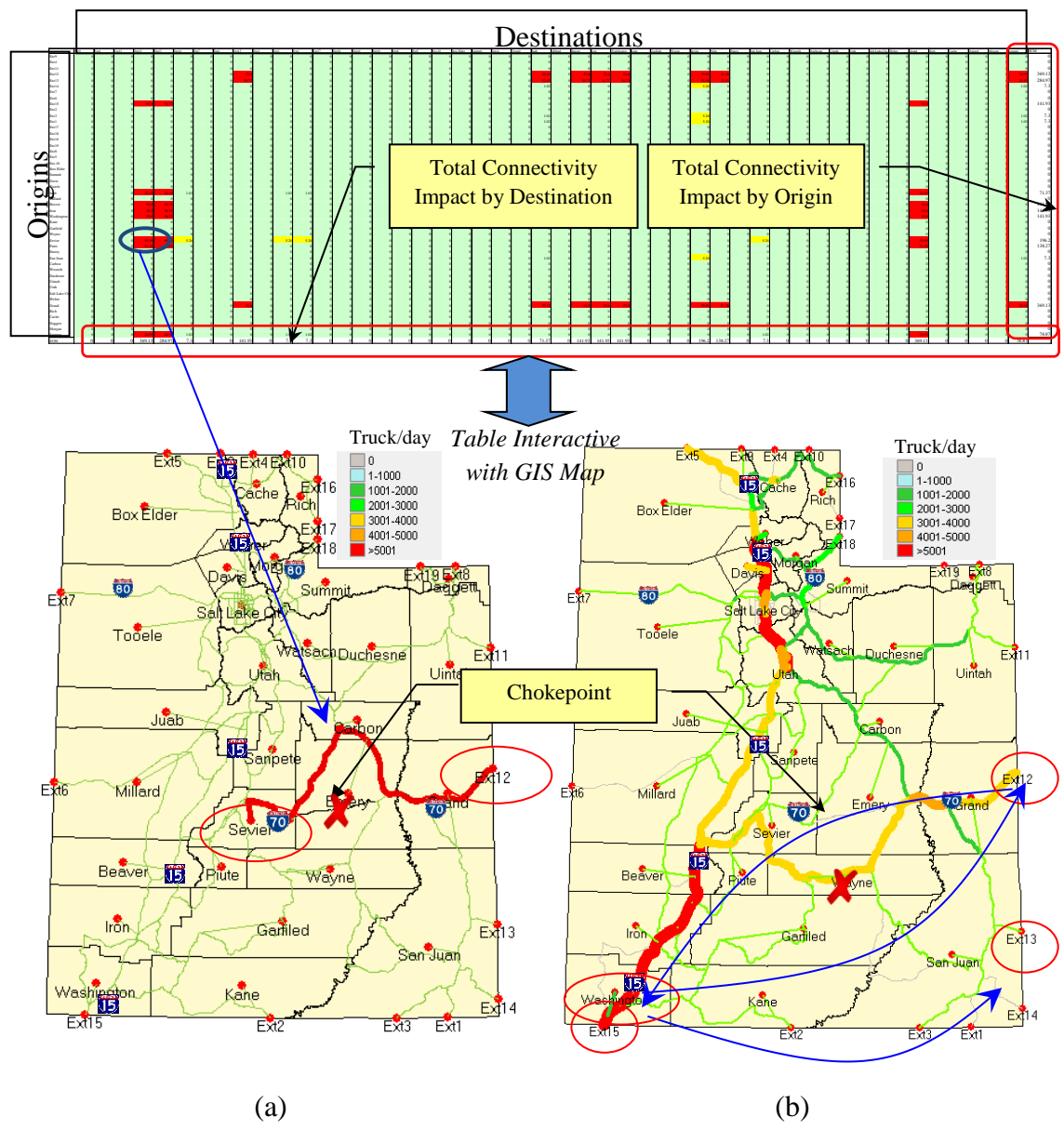
Fig. 4.7a) Detour route of Scenario A b) Freight flow pattern and top three affected
O-D pairs

As expected, the disruptions of urban bridges in Fig. 4.8b impact mostly on the

intrastate trips especially in Salt Lake and Utah counties. Interestingly, the disruption of

bridges in the rural areas have affected not only the counties in the rural areas (i.e.,

Beaver, Iron and Washington counties) but also many other counties in the metropolitan areas including Salt Lake, Davis, Weber, Utah, and Cache counties (shown in the dash circle). They also impact some external stations (e.g., I-15S, I-70E, and I-80E). This is because the metropolitan areas are the major origins and destinations for freight transportation, specifically for the production flows from Utah going to other states (i.e., I-E truck trips), and attraction flows from other states going to Utah (i.e., E-I truck trips). Hence, the multiple disruption results could be useful to the state DOT and city/county agencies in preparing the *multi-jurisdictional pre-disaster plan* and identifying ways to minimize the propagated consequences of disaster occurring in multiple jurisdictions. Fig 4.9 depicts the results of economic loss for eight scenarios by origin (Fig 4.9a) and by destination (Fig 4.9b).

(a)   (b)
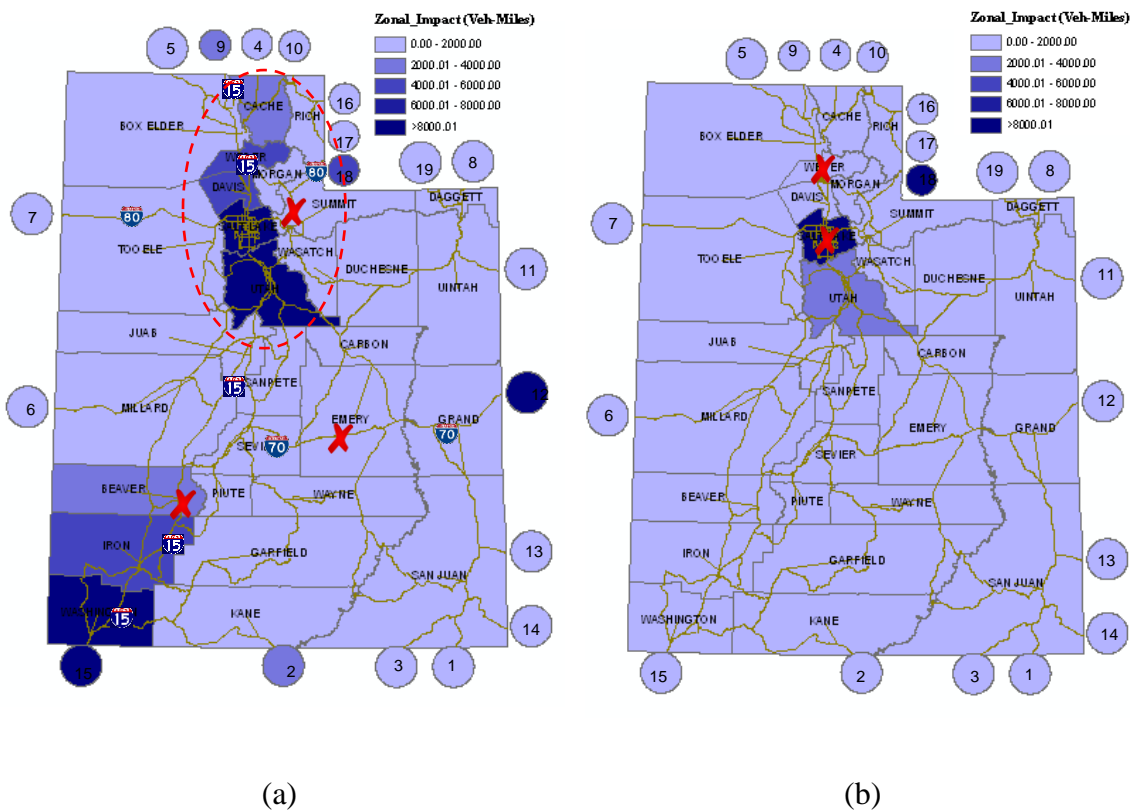
Fig. 4.8 a) Zonal impact of Scenario F b) Zonal impact of Scenario G

To make the economic impact measures easier for comparison among scenarios, we normalize the zonal economic impacts using the sum of the total economic impacts by origin (E_c^{origin}) and by destination ($E_c^{destination}$) (i.e., $E_c^{origin} / \sum_c E_c^{origin}$, $E_c^{destination} / \sum_c E_c^{destination}$). The results are presented as the percentage of economic impacts by zone. As can be seen, the economic impacts are concentrated on the metropolitan areas and some of major external stations at the state borders. This is expected because the economic impacts directly relate to truck demand.

(a)   (b)
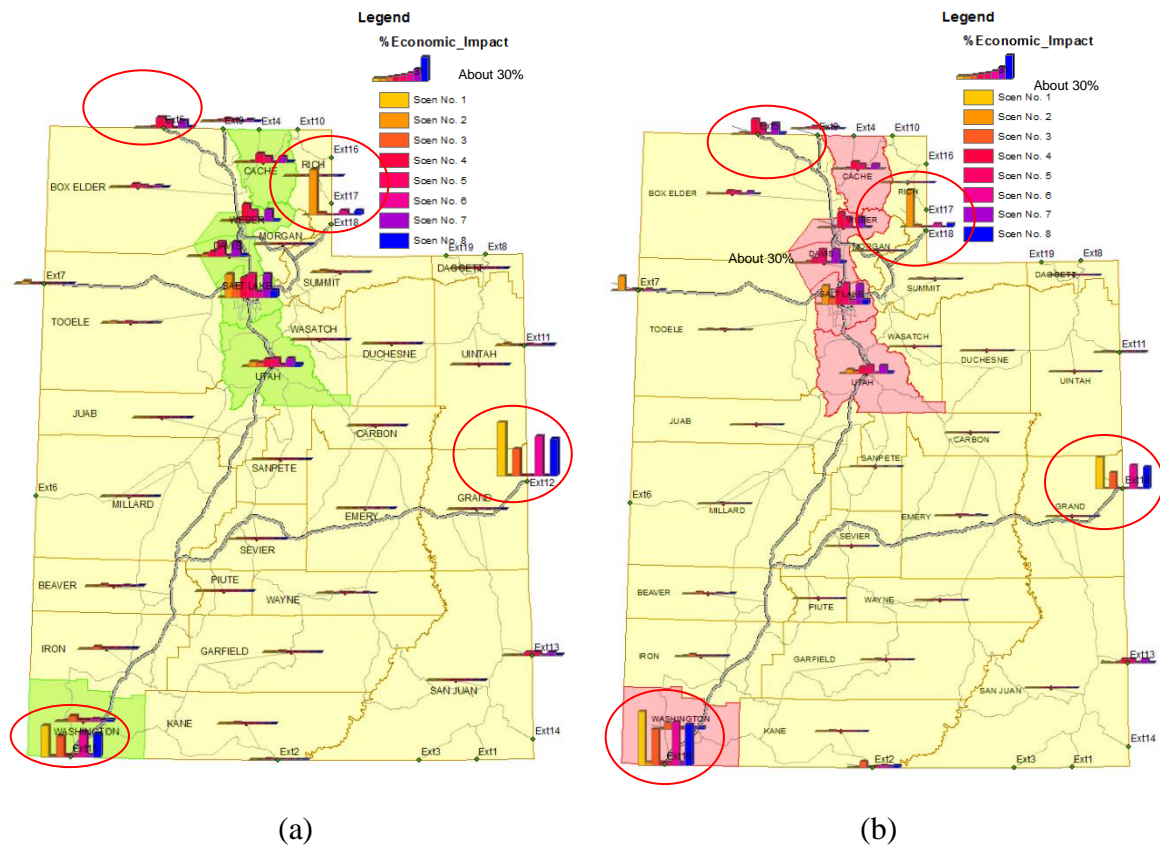
Fig 4.9 Economic impacts of all scenarios a) by origin and b) by destination

In general, the metropolitan areas with more commercial units, industries and warehouses will be directly affected by the disruptions within their area (I-I truck trips) as well as those that are originating or destined from the affected zones (I-E and E-I truck trips). Motorist information of alternate route in the urban area is important as it can assist truck drivers to divert from the disrupted area. In the case of interstate traffic, the impacts are highly related to the network topology and locations of the disruption. The results of freight flow pattern change and economic impacts are summarized in Table 4.2 and Table 4.3, respectively. As can be seen in Table 4.2, the counties that have the highest increased distances caused by the single disruptions in rural area (i.e., Scenario C) and urban area (i.e., Scenario E) are Garfield County and Duchesne County, respectively. These two counties also have the greatest impacts for the multiple-disruption scenarios. Results based on the pure topological viewpoint indicate that these two counties require special attentions as the accessibility to these counties are severely limited.

The results in Table 4.3, however, indicate that the external station 12 at I-70E and external station 15 at I-15S (i.e., Scenario A) and Salt Lake County (i.e., Scenario E) have the highest freight flow pattern change, and total economic impacts. In particular, the highest total economic loss of Scenario A (i.e., 343,870 USD/day), implies the criticality of this chokepoint to Utah freight transportation network. The structural improvement schemes of this particular bridge to withstand the disruption are recommended.

Table 4.2: Results of O-D connectivity for all scenarios

Scenario	Disruption/ Area Types	O-D Connectivity		
		Maximum Impacted Zone	Maximum Impacted Detour (mile)	Total Network Detour (mile)
A	Single/Rural	Beaver County	369.13	2,104.9
B	Single/Rural	Cache County	1,427.44	1,375.1
C	Single/Rural	**Garfield County**	**1,758.66**	**9,413.5**
D	Single/Urban	Weber, Rich, Emery County	12.32	89.6
E	Single/Urban	**Duchesne County**	**84.40**	**1,394.7**
F	Multiple/Rural	Garfield County	1,950.95	12,756.7
G	Multiple/Urban	Duchesne County	88.80	1,484.3
H	Multiple/Rural+Urban	Garfield County	1,955.35	14,332.2

Table 4.3: Results of freight flow pattern change and total economic impact for all scenarios

Scenario	Disruption/ Area Types	Freight Flow Pattern Change					Total Economic Impact
		Maximum Impacted by Origin	Freight Flow Pattern Change (veh-mile)	Maximum Impacted by Destination	Freight Flow Pattern Change (veh-mile)	Total Network Flow Change (veh-mile)	(USD./day)
A	Single/Rural	**Ext. 12 (I-70 E)**	**124,066.10**	**Ext. 15 (I-15 S)**	**123,848.80**	**198,768.90**	**343,870.19**
B	Single/Rural	Ext. 18 (I-80 E)	12,019.80	Ext. 18 (I-80 E)	9,700.90	22,796.90	39,438.56
C	Single/Rural	Ext. 12 (I-70 E)	31,948.70	Ext. 15 (I-15 S)	42,596.00	101,482.50	175,564.78
D	Single/Urban	Salt Lake County	187.10	Salt Lake County	155.10	824.90	1,427.06
E	Single/Urban	**Salt Lake County**	**4,980.80**	**Salt Lake County**	**4,309.10**	**18,128.70**	**31,362.61**
F	Multiple/Rural	Ext. 12 (I-70 E)	132,035.00	Ext. 15 (I-15 S)	143,333.70	284,714.00	492,555.19
G	Multiple/Urban	Salt Lake County	5,167.90	Salt Lake County	4,464.30	18,953.60	32,789.65
H	Multiple/Rural+Urban	Ext. 12 (I-70 E)	132,098.20	Ext. 15 (I-15 S)	143,362.20	304,809.80	527,320.92

4.5   Conclusions and future research

The primary objective of this research was to develop a decision support system (DSS) tool for assessing vulnerability of freight transportation networks. The state-specific commodity flows within, out of, into, and through Utah were extracted from the freight analysis framework (FAF) database and then converted into truck trips to generate a truck origin-destination (O-D) trip table. The results were encouraging in the sense that the commodity flow data from the FAF database could be used to estimate the statewide truck demand. A DSS tool was developed with GIS functionalities, an open source code GIS program, and a graphical user interface (GUI) to facilitate user inputs, vulnerability assessment, and visualization of the outputs. To demonstrate the applicability of the DSS tool, a case study based on the disruption of structurally deficient bridges in the Utah highway network was conducted. Results of the vulnerability assessment in terms of O-D connectivity, freight flow pattern changes, and economic impacts were reported.

In general, disruptions to the rural bridges significantly increase the travel distance (taking a long detour) due to the limited alternative routes in the rural area, while disruptions to the urban bridges would alter the freight flow pattern as indicated by the increase in VMT in the urban area. In addition, disruptions to multiple bridges could have a much higher impact in terms of travel distance and VMT compared to the single bridge failure scenario. The *what-if* analysis in the DSS allows planners, stakeholders, and citizens to determine *what* would be the potential consequences such as supply shortage or any freight transportation failure *if* the chokepoint disruptions happen allowing them to prepare ahead of time for handling such events. The results of the DSS can be also used by state DOT to support infrastructure investment schemes (e.g., maintenance of aging

infrastructure, enhancement of capacity, design for new roads) in order to reduce network vulnerability. Motorist information of alternate route should be provided to assist truck drivers to divert from the disrupted area (i.e., in urban area) or plan for alternative route before entering the state (i.e., in rural area), hence reducing the potential impacts due to chokepoint disruption. Information technology such as live traffic map, emergency alert should be further integrated to the DSS as it could help truck driver to plan for alternative routes or set up for alternative travel itinerary (e.g., delay the shipment or seek for alternative transportation modes). The results suggest that developing a pre-disaster statewide plan that coordinate multiple jurisdictions (state DOT and city/county agencies) could be helpful in minimizing the potential economic losses. In particular, the state DOT should develop a partnership with the neighboring states DOT to create a seamless information backbone for freight transportation (e.g., I-15 Mobility Alliance by the Departments of Transportation in California, Nevada, Arizona, and Utah (CH2MHILL, 2012)) and establish the preparedness and coordination plan.

Potential recommendations for future research include the following: (1) truck O-D trip table improvement and (2) DSS enhancement. The current truck O-D trip table is estimated purely from the commodity flow data from FAF. It should be updated using the newly developed Utah Statewide Travel Model (USTM) to improve the accuracy and quality of the truck O-D trip table. The DSS tool should be enhanced according to the user's feedback as recommended by Yoon *et al*. (2008). It could also be used to guide longer-term decisions involving resource allocation to fortify critical infrastructure as well as for improving freight transportation networks (e.g., truck corridors) to withstand future disasters. An optimization approach introduced by Murray *et al*. (2007) to identify

the critical chokepoints, particularly based on the concept of network flow interdiction approach could be integrated in the future DSS tool. The potential applications of the proposed DSS tool could be used to prioritize the structurally deficient bridges for maintenance and retrofitting, estimating the economic impacts based on commodity values, integrating the DSS tool to consider vulnerability assessment analysis as part of the statewide planning model.

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CHAPTER 5

MEASURING REDUNDANCY OF FREIGHT TRANSPORTATION NETWORKS

Abstract

Freight transportation network is an essential backbone for supporting the industrial activities and economic developments of the nation and global trade. In this study, we develop a quantitative approach for assessing the redundancy of freight transportation networks, one of the four "Rs" (Robustness, Redundancy, Resourcefulness, and Rapidity) for calculating the resiliency triangle. Redundancy is characterized by two main dimensions: route diversity and network spare capacity. The route diversity dimension is to evaluate the existence of multiple efficient routes available for freight users or the degree of connections between a specific origin-destination (O-D) pair. The network spare capacity dimension is used to quantify the network-wide spare capacity of multimodal freight transportation networks with an explicit consideration of congestion effect. These two dimensions can complement each other by providing a two-dimensional characterization of freight transportation network redundancy. For illustration purpose, a hypothetical network is employed first to demonstrate the complementary effects of the two main dimensions. Two case studies of the Utah statewide and multimodal coal transportation networks are provided to demonstrate the features of the two-dimensional approach as well as the applicability of the evaluation methodology.

5.1   Introduction

Freight transportation network is an essential backbone for supporting the industrial activities and economic developments of the nation and global trade.

Disruption to these networks due to natural disasters or manmade malicious acts can seriously cripple the region's economic productivity. The adverse consequences of recent disasters around the world have demonstrated the importance of these networks to the functioning of modern society, and yet they are so fragile. It is important for government agencies to make the system more robust and resilient to withstand the anticipated and unanticipated losses. The United States Department of Transportation (USDOT), for instance, has considered the concept of resiliency into the National Transportation Recovery Strategy (USDOT, 2009). The overall goal of this strategy is to enhance the recovery process of transportation networks under disruptions, and subsequently to increase the level of resiliency of various infrastructures in the community. Although there is no universal definition of resiliency, various conceptual frameworks and measures have been proposed for analyzing transportation network resiliency, e.g., Caplice *et al*. (2008), Goodchild *et al*. (2009), Ortiz *et al*. (2009), Ta *et al*. (2009), Cox *et al*. (2011), Ip and Wang (2011), Urena *et al*. (2011), Adams *et al*. (2012), Faturechi and Miller-Hooks (2013), and Omer *et al*. (2013).

Engineers and social scientists at the Multidisciplinary Center for Earthquake Engineering Research (MCEER) have proposed a framework for defining resiliency (Bruneau *et al*., 2003). This study characterizes resiliency based on the four "Rs" concept:

- Robustness refers to strength, or the ability of elements, systems, and other units of analysis to withstand a given level of stress or demand without suffering degradation or loss of function;

- Redundancy refers to the extent to which elements, systems, or other units of analysis exist that are substitutable, i.e., capable of satisfying functional requirements in the event of disruption, degradation, or loss of function;

- Resourcefulness refers to the capacity to identify problems, establish priorities, and mobilize resources when conditions exist that threaten to disrupt some element, system, or other unit of analysis; and

- Rapidity refers to the capacity to meet priorities and achieve goals in a timely manner in order to contain losses and avoid future disruption.

Despite a growing body of research on transportation network resiliency, very few have developed quantitative measures to assess the four "Rs" concept described above, and even less likely to focus on freight transportation networks. In this research, we initiate an attempt to quantitatively assess the *redundancy* of freight transportation networks, one of the four "Rs" suggested by Bruneau *et al*. (2003) for calculating the resiliency triangle. Redundancy is an important indicator in the development of an emergency response and recovery plan (FHWA, 2006). A typical pre-disaster planning strategy is to improve network resiliency by adding redundancy (e.g., new roadways) to create more alternatives for users or by hardening the existing infrastructures (e.g., retrofitting existing bridges) to withstand disruptions. Ortiz *et al*. (2009) suggested several redundant strategies to enhance freight transportation network resiliency, including directing freight traffic to pre-identified alternative routes, repairing infrastructures after a disaster to limit the effect of a disruption, and adding capacity (e.g., additional lanes, intermodal connection capacity, or bridges at river crossings) at critical intermodal connections. Ortiz *et al*. (2009) further suggested that the system can build

resiliency by managing two network properties: *vulnerability* and *adaptive capacity*. The vulnerability is the ease with which a disturbance may cause a system to deviate from its normal behavior. The adaptive capacity is the ability of a system to devote resources to respond to a disturbance, and thereby can reduce the magnitude and extent of adverse consequences. A similar concept to adaptive capacity is *capacity flexibility* (e.g., Morlok and Chang (2004) for freight transportation and Chen and Kasikitwiwat (2011) for passenger transportation), which is defined as the ability of a transport system to accommodate changes in traffic demands, while maintaining satisfactory system performance.

Further, Transystems (2011) pointed out the importance of redundancy as one of the resiliency measures in their statewide freight resiliency plan. A redundant system, in their view, should focus on the availability of alternative routes and/or modes. In general, a freight highway system consists of three major components: primary, secondary, and connector highway routes (see Fig. 5.1 for an illustration). Specifically, a primary highway route is defined as a physical route representing a key freight corridor with statewide significance, and connecting major activity nodes within a state. A secondary highway route is an alternative route to the primary highway route, usually a state route or frontage road parallel to the Interstate freeway connecting the same major activity nodes. In addition, an alternative mode, such as rail, can provide mode choice opportunities (e.g., rail only, truck-rail, rail-truck, and truck-rail-truck) to transport freight shipments.

With this structure, a diverse set of routes and modes is formed to provide various alternatives in case that the primary and/or secondary routes are not available during a
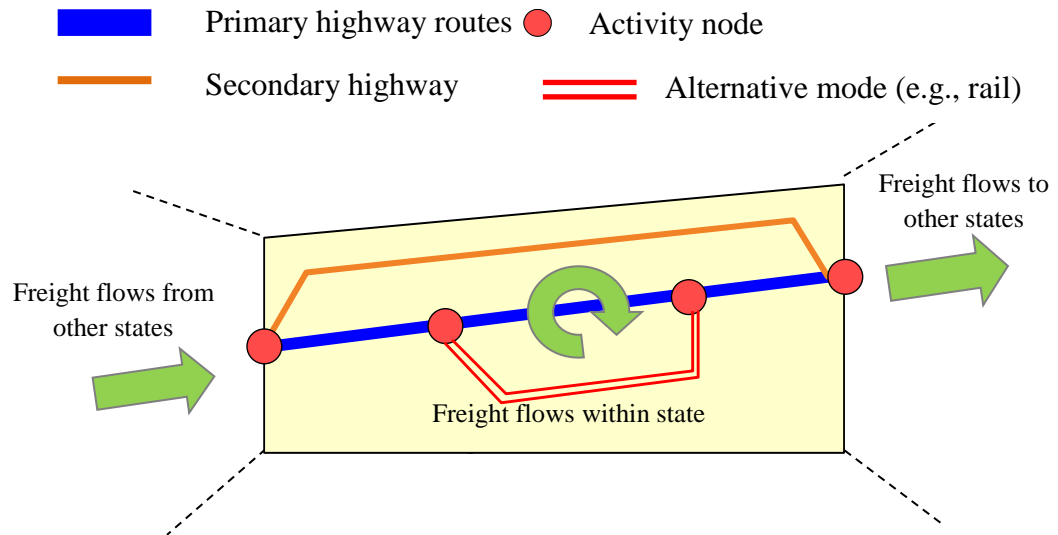
Fig. 5.1 Statewide freight highway system: primary, secondary routes, and alternative mode
(Adapted from Transystems, 2011)

disruption. However, measuring only the diversity of alternative routes and modes may overlook the effect of diverting or rerouting traffic to the alternative routes or other transportation modes. Large amount of diverting trucks can clog traffic on bottlenecks along the secondary and connector routes, and consequently degrade the level of service of network. In order to adequately capture these characteristics, network spare capacity should also be explicitly considered in freight network redundancy characterization.

Additionally, we note that the flexibility to alter the operations by shifting goods to alternative routes or modes is an important factor in enhancing freight network redundancy. For example, a multimodal transportation system can be viewed as a redundant system, especially when the primary mode is not available during a disaster, as it provides alternative modes to transport freight shipments (e.g., diverting from truck to rail, truck to barge, and so on). In the normal event, a multimodal transportation could

also play an important role in reducing network congestion because of the benefit of the *joint-use* capacity.

In this study, we develop two quantitative measures for assessing freight transportation network redundancy – an important component in making freight transportation networks more robust and resilient against disruptions. Redundancy of freight transportation networks is characterized by two main dimensions: route diversity and network spare capacity. Specifically, the *route diversity dimension* is to evaluate the existence of multiple efficient routes available for freight users or the degree of connections between a specific origin-destination (O-D) pair. The *network spare capacity dimension* is used to quantify the *network-wide* spare capacity with an explicit consideration of congestion effect. These two dimensions can complement each other by providing a two-dimensional characterization of freight transportation network redundancy. The proposed two-dimensional approach can be used to provide information to freight users (i.e., truck drivers, freight carriers, etc.) as well as to assist network planners in making future infrastructure investment decisions to enhance the redundancy of freight transportation networks.

The remainder of this chapter is organized as follows. The next section reviews the concept of redundancy used in different disciplines and specifically in freight transportation networks. Section 5.3 presents the two measures and the evaluation methodology for assessing redundancy of freight transportation networks. Section 5.4 then demonstrates the features of the two-dimensional approach as well as the applicability of the evaluation methodology using the Utah statewide and multimodal

coal transportation networks as case studies. Finally, conclusions are summarized in Section 5.5.

5.2   Literature review

5.2.1   *Some useful redundancy concepts*

The concept of redundancy has been studied in different disciplines including reliability engineering, water distribution system, computer network, the internet, and so on. The Webster/Merriam Dictionary (2012) gives a general definition of redundancy (or state of redundant) as: (1) exceeding what is necessary or normal, or (2) serving as a duplicate for preventing failure of an entire system upon failure of a single component. In reliability engineering, redundancy is the existence of more than one means for accomplishing a given function, and each means of accomplishing the function is not necessarily identical (O'Connor, 2010). Redundancy in water distribution system is defined as the existence of alternative pathways from the source to demand nodes or excess capacity in normal operating conditions when some components of the system become unavailable (Kalungi and Tanyimboh, 2003). According to the above definition, there are two types of redundancy measures: (a) active redundancy, and (b) standby redundancy. The active redundancy is the redundancy where all redundant items are operating simultaneously rather than being switched on when needed. On the other hand, the standby redundancy is the redundancy where the alternative means of performing the function is inoperative until needed and is switched on upon failure of the primary means of performing the function. In structural engineering, redundancy is the ability of a structural system to redistribute stresses to its members/connections and thereby ensuring the safety of structural systems. According to Fang and Fan (2011), the redundant

structures can assist in: (1) enhancing the safety margin/reliability of a structure in its intact state; and (2) mitigating the sensitivity/vulnerability of the structure to localized damage under an accidental situation.

Redundancy is also a well-known concept in computer science, especially for the Internet. The Internet was designed to make use of the redundancy embedded in the network structure (Wheeler and O'Kelly, 1999). When the primary network encounters a disruptive event (e.g., natural disaster or man-made incident), the internet service providers (ISPs) automatically implement rerouting strategy to reroute traffic to redundant connections. Typically, the goal of a redundant internet network aims to minimize the *downtime* (or negative impact) to ensure service reliability. In addition, many businesses today implement a *backup system* (i.e., secondary connection) which is totally independent of the primary network to reduce the outage effect. In the context of graph theory, various measures were introduced to analyze network efficiency by expressing the relationship between the network structure and its properties. Rodrigue *et al*. (2009) summarized some useful indices for measuring network efficiency. For example, they used the alpha index to measure network connectivity and network redundancy (i.e., alpha index$=(e-v+1)/(2v-5)$, where e is the number of links, and v is the number of nodes in a network). The alpha index, ranging between 0 and 1, indicates the degree of network connectivity. An alpha value of 1 represents a highly redundant network, while a value of 0 indicates redundancy is non-existence. In logistics and supply chain, Sheffi and Rice. (2005) suggested that flexibility and redundancy are key factors to achieve resiliency. The redundancy is related to the concept of safety stock, underutilized capacity or inventory in reserve to be used in case of disruption, while

flexibility, in their perspective, can help a company (or a supplier) not only to withstand significant disruption but also respond to demand fluctuations, thus increasing its competiveness.

5.2.2   *Redundancy in transportation networks*

Berdica (2002) firstly developed a framework and basic concepts for vulnerability and many neighboring terms such as resiliency and redundancy. According to Berdica (2002), redundancy is "the existence of numerous optional routes/means of transport between origin and destinations can result in less serious consequences in case of a disturbance in some part of the system". From her viewpoint, redundancy is related to the system diversity that can be used to handle a network disturbance. Few researchers have introduced measures for assessing the resiliency of transportation networks and redundancy is one of those measures. For example, Godschalk (2003) and Murray-Tuite (2006) defined redundancy as the number of functionally similar components which can serve the same purpose, and hence the system does not fail when one component fails. A relevant concept of redundancy is *diversity*, which refers to a number of functionally different components that protect the system against various threats (e.g., alternative transport modes). Similarly, Goodchild *et al*. (2009) introduced redundancy as one of the desired properties of freight transportation resiliency. They defined redundancy as the availability of multiple alternate routing options in the freight transportation network. Jenelius (2010) recently proposed the concept of redundancy importance to consider the importance of links as backup alternatives when other links in the network are disrupted. Two measures (i.e., flow-based and impact-based) were proposed to quantify the redundancy importance. The flow-based measure considers a net traffic flow that is

redirected to the backup links and the impact-based measure considers an increased travel time (cost) due to the rerouting effect. However, these two measures assess only the localized redundancy importance of a transportation network. In other words, they are not able to capture the diversity of alternatives, an important property for measuring network redundancy. In our study, we propose a two-dimensional approach to assess redundancy: (1) *route diversity*, and (2) *network spare capacity*. We argue that the *diversity of available routes and modes* when the primary choice is inoperative needs to be explicitly considered in the redundancy characterization. However, the route diversity alone may not be a sufficient measure of redundancy as it lacks the interaction between transport demand and supply (i.e., congestion effect due to limited network capacity). Congestion effect and freight shippers' decisions in route and mode choices are two critical characteristics of freight transportation networks. In order to adequately capture these two characteristics, network spare capacity should also be explicitly considered in freight network redundancy characterization.

5.3   Methodology

Our assessment approach is developed based on two dimensions: route diversity and network spare capacity. A quantitative approach to evaluate these two measures is described in this section.

5.3.1   Dimension 1: route diversity

Route diversity refers to the existence of multiple routes available for freight users (or the degree of connections) between a specific O-D pair. There are several definitions of a route including simple route (i.e., a route without repeated nodes), efficient route (Dial, 1971), and distinct route (Kurauchi *et al.*, 2009). In this research, we focus on the

concept of efficient routes (also called reasonable routes) and how to measure route diversity by counting the number of efficient routes.

5.3.1.1 *Efficient routes*

The definition of efficient routes is a route that includes only links that make the users further away from the origin and/or closer to the destination. This concept adopts Dial's method (Dial, 1971) to identify the efficient routes according to the logit model. Mathematically, a route $r \rightarrow n_1 \rightarrow n_2 \rightarrow \ldots \rightarrow n_k$ is an efficient route, if and only if

$$l_r(n_{i+1}) > l_r(n_i), \ i=1, 2,\ldots, K\text{-}1, \tag{5.1}$$

where $l_r(n_i)$ is the shortest route cost from origin r to node n_i, and K is the number of the intermediate nodes. Meng *et al*. (2005) developed a combinatorial algorithm with *polynomial-time* complexity to count the number of efficient routes between an O-D pair. This algorithm consists of two parts: (1) constructing a sub-network for each origin r, $G_r = (N_r, A_r)$, and (2) counting the number of efficient routes from origin r to all nodes in the sub-network $G_r = (N_r, A_r)$. The sub-network $G_r = (N_r, A_r)$ is a connected and acyclic network, which is used to identify the efficient routes (i.e., the sub-network only includes the links that are on the efficient routes from this origin). The procedures of constructing the sub-network and counting the number of efficient routes are described as follows:

Constructing the sub-network $G_r = (N_r, A_r)$

For each origin r

Perform a shortest path algorithm to find the minimum cost from origin r to all nodes,

$l_r(n), \ n \neq r$

For all nodes $n \neq r$

If $l_r(n) = \infty$

Then $N_r = N_r \backslash \{n\}$

For all links a

If $l_r(tail_a) \geq l_r(head_a)$ (where $tail_a$ and $head_a$ are the tail and head of link a)

Then $A_r = A_r \backslash \{a\}$

Counting the number of efficient routes from origin r to all nodes

Input: tail node and head node of all links $(tail_a, head_a)$, $a \in A_r$

Step 1 Initialization:

u=0($|N_r|$, $|N_r|$)

For all links $a \in A_r$

$u(tail_a, head_a)$=1

Step 2 Matrix Operations:

For all nodes $j \in N_r$

For all nodes $m \in N_r \backslash j$

For all nodes $n \in N_r \backslash j \backslash m$

$u(m, n) := u(m, n) + u(m, j) \times u(j, n)$

Output: $u(r, n)$: the number of efficient routes from origin r to all nodes in the sub-network

5.3.1.2 *Demand-weighted route diversity*

We use K_{rs} to denote the set of available routes connecting a generic O-D pair (r,s), and $|K_{rs}|$ to denote the cardinality of this set. A route consists of a set of links, which are characterized by zero-one variables denoting the state of each link (operating or

failed). If there is only one route between O-D pair (r,s), i.e., $|K_{rs}|=1$, this route will be completely disconnected when one or more links on this single route is failed. Note that more available routes correspond to more opportunities for rerouting when encountering link failures. Hence, it is important for planners to provide multiple routes between an O-D pair, particularly for the important O-D pairs (to/from business activity nodes). Typically, they are O-D pairs with a large amount of freight shipments. Note that the above definition of route diversity is at an O-D pair level. We can aggregate them to higher levels (i.e., zonal-level by origin, zonal-level by destination, and network-level) for different evaluation purposes:

O-D level ♦ O-D pair (r,s): $\left|K_{rs}\right|$

Zonal level ♦ Origin r: $\left|K_r\right| = \sum_s \dfrac{q_{rs}}{\sum_s q_{rs}} \left|K_{rs}\right| = \dfrac{\sum_s q_{rs}\left|K_{rs}\right|}{O_r}$

♦ Destination s: $\left|K_s\right| = \sum_r \dfrac{q_{rs}}{\sum_r q_{rs}} \left|K_{rs}\right| = \dfrac{\sum_r q_{rs}\left|K_{rs}\right|}{D_s}$

Network (or area) level ♦ Network: $\left|K\right| = \sum_r \dfrac{O_r}{\sum_r O_r} \left|K_r\right| = \dfrac{\sum_r O_r\left|K_r\right|}{\sum_r O_r}$

$$= \sum_s \dfrac{D_s}{\sum_s D_s} \left|K_s\right| = \dfrac{\sum_s D_s\left|K_s\right|}{\sum_s D_s},$$

where q_{rs} is the freight demands between O-D pair (r,s); O_r and D_s are the freight demands generated from origin r and attracted to destination s, respectively. $|K_r|$, $|K_s|$, and $|K|$ denote the degree of connections of origin r, destination s, and the whole network, respectively.

5.3.2   Dimension 2: network spare capacity

5.3.2.1 <u>Reserve capacity model</u>

The route diversity dimension is assessed based on the network topological characteristics. However, *congestion* is an important characteristic of transportation networks. In order to adequately capture the congestion effect, we consider network spare capacity as the second dimension of network redundancy. The definition of network spare capacity is based on adopts the reserve capacity concept originally proposed by Wong and Yang (1997) for a signal-controlled road network, which is defined as the largest multiplier μ applied to a given existing O-D demand matrix $\mathbf{q}$ that can be allocated to a network without violating a pre-specified level of service (LOS). This measure provides useful information about the maximum change in demand volume that can be accommodated by the current network. Mathematically, finding the network reserve capacity multiplier μ can be formulated as the following bi-level programming problem:

$$\max Z_1 = \mu \tag{5.2}$$

s.t. $$v_a\left(\mu\mathbf{q}\right) \le \theta_a C_a, \ \ \forall a \in A, \tag{5.3}$$

where A is the set of highway links; θ_a is a parameter denoting the pre-specified level of service (LOS) required on link a; C_a is the capacity of link a; $v_a\left(\mu\mathbf{q}\right)$ is the flow on link a, which is obtained by solving the traffic assignment problem at the lower level (i.e., the user equilibrium (UE) problem) under a given reserve capacity multiplier μ:

$$\min_{\mathbf{v}(\mu\mathbf{q})} \ Z_2 = \sum_{a\in A}\int_0^{v_a} t_a\left(w\right)dw \tag{5.4}$$

$$\sum_{k \in K_{rs}} f_k^{rs} = \mu \cdot q_{rs}, \quad \forall r \in R, s \in S, \tag{5.5}$$

s.t.

$$v_a = \sum_{r \in R} \sum_{s \in S} \sum_{k \in K_{rs}} f_k^{rs} \delta_{ak}^{rs}, \quad \forall a \in A, \tag{5.6}$$

$$f_k^{rs} \geq 0, \quad \forall k \in K_{rs}, r \in R, s \in S, \tag{5.7}$$

where R and S are the sets of origins and destinations, respectively; t_a is the travel time on link a; f_k^{rs} is the flow on route k between O-D pair (r,s); δ_{ak}^{rs} is the link-route incidence indicator: $\delta_{ak}^{rs}=1$ if link a is on route k between O-D pair (r,s), $\delta_{ak}^{rs}=0$ otherwise. In this formulation, the objective function in Eq. (5.2) is to maximize the multiplier μ; Eq. (5.3) is the link LOS constraint; Eqs. (5.4) to (5.7) describe the UE traffic assignment problem (Beckmann *et al.*, 1956; Sheffi, 1985); Eq. (5.4) is the well-known Beckmann's transformation; Eq. (5.5) is the demand conservation constraint; Eq. (5.6) is a definitional constraint that sums up all route flows that pass through a given link; and Eq. (5.7) is a non-negativity constraint on the route flows. The largest value of μ indicates whether the current network has spare capacity or not. For example, if $\mu>1$, then the current network has a reserve (or spare) capacity amounting to $100(\mu-1)$ percent of the existing O-D demand **q**; otherwise, the current network is overloaded by $100(1-\mu)$ percent of **q**. In this study, we use an incremental assignment-based method to determine the network spare capacity of a transportation network (see Sheffi (1985) for details of this procedure).

5.3.2.2 *Multimodal network spare capacity models*

Multimodal transportation refers to a transportation system that encompasses both the unique and shared functionality of its component modes (e.g., air, water, truck, and rail) and of its facilities for exchanging traffic among and between modes (e.g.,

warehouse/distribution centers, rail terminals, seaports, airports) (Cambridge Systematics, Inc., 2007). Because freight transportation is highly competitive, freight shippers generally choose the most cost effective mode to transport large quantities of containerized cargos or bulk commodities (e.g., grains, coals, construction materials, etc.). Mode of freight transportation can also be shifted from truck to rail, or from truck to barge due to several reasons. One reason is the operational efficiency in terms of cost and its economy of scale especially for bulk commodities. Another reason is changes in demand pattern due to unusual events (e.g., disasters, strikes). During a disastrous event, the highway system can be extremely congested or some links are even impassible because of road closures. It can take several hours, days, or weeks to bring the system back to normal. Meanwhile, freight shippers have to seek for alternative ways by using alternate routes or shifting to alternate mode in order to respond to their shipping requirements.

Hence, a multimodal transportation system can be viewed as a redundant system. Specifically, it adds spare capacity to the current system, and will operate or switch on upon failure of the primary modes. Fig. 5.2 provides an illustration of a multimodal transportation system that can be considered as a key support for freight network redundancy.   As can be seen, there are multiple possible ways to ship goods from different origins to different destinations, which can help to not only increase network capacity but also improve the system diversity.

When estimating the network-wide capacity of a multi-modal system (e.g., truck-rail network), we need to explicitly consider roadway, railway, and zonal physical
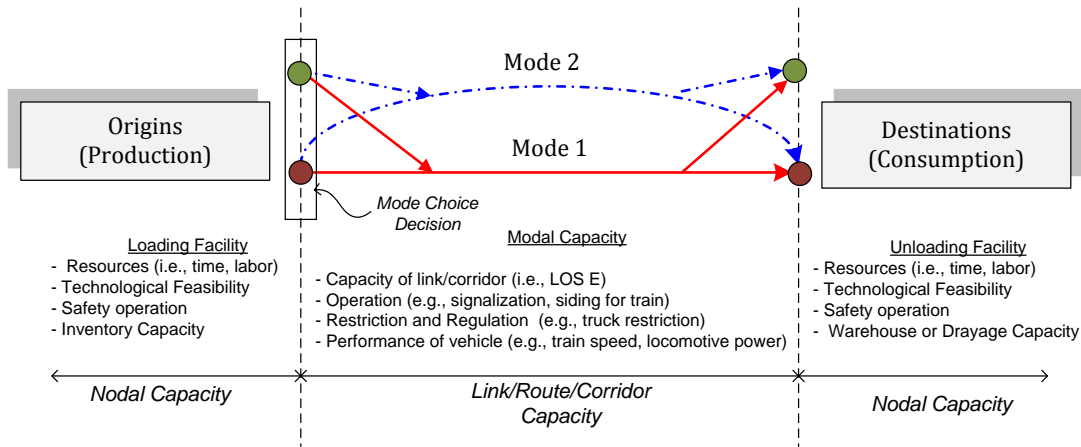
Fig. 5.2 Illustration of a multimodal transportation system for supporting network redundancy

capacity constraints. The zonal capacity is exemplified by the capacity of loading and unloading facilities, yards, and terminals that the freight would be handled at. According to the NCHRP Report No. 399 (Cambridge Systematics, Inc., 1998), the zonal capacity is also related to the safe and feasible technology operated at the facilities.

In this research, we develop two models for assessing the spare capacity of a multimodal freight network. The first model is developed based on the network reserve capacity model for a single mode. The upper level problem is modified to address the logistical constraints of an additional mode. Let us consider rail transportation as an additional mode to our freight network. Typically, the railway logistical problem is often constrained by the capacity of rail corridors (or routes), loading, unloading activities, and storage capacity at the origins and destinations. The upper level problem of this bimodal freight network capacity problem can be formulated as:

$$\max\ Z_3 = \mu \tag{5.8}$$

s.t.
$$v_a(\mathbf{q}^{truck}) \leq \theta_a C_a, \forall a \in A, \tag{5.9}$$

$$q_{rs}^{rail} \leq \phi H_{rs}^{rail,\max}, \forall r \in R, s \in S, \tag{5.10}$$

$$\sum_{s \in S} q_{rs}^{truck} + \sum_{s \in S} q_{rs}^{rail} \leq o_r^{\max}, \forall r \in R, \tag{5.11}$$

$$\sum_{r \in R} q_{rs}^{truck} + \sum_{r \in R} q_{rs}^{rail} \leq d_s^{\max}, \forall s \in S, \tag{5.12}$$

$$q_{rs}^{rail}, q_{rs}^{truck} \geq 0, \forall r \in R, s \in S, \tag{5.13}$$

where $\mathbf{q}^{truck}$ is a truck O-D demand matrix, q_{rs}^{rail} is rail O-D demand between O-D pair *(r,s)*. Note that these O-D demands are the results of the existing total demand pattern demand $\tilde{\mathbf{q}}$ uniformly scaled by μ (to be shown in Eq. (5.20)). $H_{rs}^{rail,\max}$ is the maximum capacity of a rail corridor between O-D pair *(r,s)*; ϕ is the truck-rail conversion factor so that they are expressed in the same unit; $o_r^{\max}$ is the maximum freight production at origin r; $d_s^{\max}$ is the maximum freight attraction at destination *s*. The railway link capacity ($H_{rs}^{rail,\max}$) between O-D pair *(r,s)* in Eq. (5.10) can be estimated based on various factors such as speed, corridor length, operation hours at terminal, number of stops, railway signals, timetable robustness, and so on. A more comprehensive literature review of previous works on railway capacity can be found in Abril *et al*. (2008). In our study, we adopt the capacity models from the NCHRP Report No. 399 (Cambridge Systematics, Inc., 1998) to estimate the railway link capacity which can be calculated based on the maximum permissible delay using the following equations:

$$H_{rs}^{rail,\max} = A_c \big/ B*(100/L),$$

<div align="right">(5.14)</div>

$$A_c = \frac{\left[\begin{array}{l} -(67.276P+151.708D)/L+ \\ \sqrt{\begin{array}{l}(67.276P+151.708D)^2/L^2- \\ (3,892,500S/L)^2*(1.41432-150M/L+150/S+I)\end{array}}\end{array}\right]L^2}{1,946,250S},$$

<div align="right">(5.15)</div>

for a single track railroad, and

$$A_c = 0.031L\sqrt{1/S(M*150/L-150/S-I-1.846)},$$

for a double-track railroad,

<div align="right">(5.16)</div>

where A_c is the average delay per train at capacity (hours) estimated from Eq. (5.15) for a single track railroad or Eq. (5.16) for a double-track railroad, B is the delay slope, L is the length of line (mile), M is the maximum allowable total running time (i.e., operation hours at terminal), S is the speed of the slowest class of through freight train (miles/hour), P is the dispatch peaking factor (trains per peak hour), D is a directional factor, and I is the amount of imposed delays on regular freight trains (e.g., required stops). It should be noted that the maximum capacity of production and attraction in Eqs. (11) and (12) are generally limited by the maximum processing rate through the node (e.g., terminal, warehouse). They are in the units of weight, cubic volume, dollar value, or equivalent equipment movements such as truckloads and containers. Eq. (5.13) is a non-negativity constraint on the O-D flows. The UE problem at the lower level is also adapted to account for the alternate mode. Particularly, the UE traffic assignment with consideration of a modal split function is applied (see Chapters 6 and 9 in Sheffi (1985) for details). The modal split function between truck and rail can be simply formulated as a logit choice function:

$$q_{rs}^{truck} = q_{rs}^{total} \frac{1}{1+e^{\theta(u_{rs}^{truck} - u_{rs}^{rail} - \Psi_{rs})}}, \forall r \in R, s \in S,$$ (5.17)

$$q_{rs}^{rail} = q_{rs}^{total} \frac{1}{1+e^{\theta(u_{rs}^{rail} - u_{rs}^{truck} + \Psi_{rs})}}, \forall r \in R, s \in S,$$ (5.18)

where q_{rs}^{total} is the total freight flows between O-D pair (r,s); u_{rs}^{truck} is the minimum travel time by truck between O-D pair (r,s); u_{rs}^{rail} is the minimum travel time by rail between O-D pair (r,s); Ψ_{rs} is a constant that captures the effect of factors other than travel time difference on the modal split function (e.g., external costs or any restrictions that may be applied). The UE formulation with the modal split function is expressed as:

$$\min Z_4 = \sum_{a \in A} \int_0^{v_a} t_a(\omega)d\omega + \sum_{r \in R}\sum_{s \in S} \int_0^{q_{rs}^{rail}} \left(\frac{1}{\beta} \ln \frac{\omega}{q_{rs}^{total} - \omega} + u_{rs}^{rail} + \psi_{rs} \right) d\omega$$ (5.19)

s.t.
$$q_{rs}^{total} = \mu \tilde{q}_{rs}^{total}, \forall r \in R, s \in S,$$ (5.20)

$$q_{rs}^{truck} + q_{rs}^{rail} = q_{rs}^{total}, \forall r \in R, s \in S,$$ (5.21)

$$\sum_{k \in K_{rs}} f_k^{rs} = q_{rs}^{truck}, \forall r \in R, s \in S,$$ (5.22)

$$v_a = \sum_{r \in R}\sum_{s \in S}\sum_{k \in K_{rs}} f_k^{rs} \delta_{ak}^{rs}, \forall a \in A,$$ (5.23)

$$f_k^{rs} \geq 0, \ \forall k \in K_{rs}, r \in R, s \in S,$$ (5.24)

$$q_{rs}^{rail}, q_{rs}^{truck} > 0, \forall r \in R, s \in S,$$ (5.25)

where Eq. (5.19) is the objective function of a combined modal split and traffic assignment problem. The first term in Eq. (5.19) is the well-known Beckmann's

transformation (i.e., summation of the integrals of the link cost functions), while the second term is the summation of the integrals of the excess demand functions. Here, the excess demand functions can be explicitly derived from the logit choice function in Eq. (5.18). Eq. (5.20) shows the relationship of total existing O-D demand ($\tilde{q}_{rs}^{total}$) between O-D pair *(r,s)* and the total future or scaled up demand (q_{rs}^{total}) between O-D pair *(r,s)*. Eqs. (5.21) and (5.22) are the demand conservation constraints. Eqs. (5.23), (5.24), (5.25) are the definitional constraints and non-negativity constraints of O-D demands by rail, and truck respectively.

It is important to note that the reserve capacity multiplier μ uniformly scales only the total existing O-D demand (i.e., Eq. (5.20)), rather than the mode-specific O-D demand. Instead, the mode choice corresponding to q_{rs}^{total} is endogenously determined by the logit model based on O-D travel times by modes and their external costs. The second model is further developed to measure the ultimate capacity or the maximum allowable freight flow demand that can be accommodated by a given multimodal freight network. The objective function in Eq. (5.8) becomes:

$$\text{Max } Z_5 = \sum_{r \in R} \sum_{s \in S} q_{rs}^{total} \tag{5.26}$$

With this objective function, we relax the common multiplier requirement in the reserve capacity model by allowing the maximum throughputs to be scaled for individual O-D pairs. Hence, the constraint in Eq. (5.20) is omitted. This network capacity represents the theoretical ultimate capacity or the upper bound that can be transported in a multi-modal transportation network.

Table 5.1: Methods, users, and applications of route diversity and network spare capacity for measuring freight network redundancy

Measures	Methods	Types of Commodity/ Freight Network	Users
Route Diversity	Counting the number of efficient routes	General freight/ statewide or regional networks	Freight shipper/carrier[a] Network planner[b]
Network Spare Capacity	Evaluating network-wide reserve capacity	General freight/ statewide or regional networks	Network planner
	Evaluating multimodal network reserve & capacity flexibility	Commodity specific/ sub-networks (e.g., truck-rail, truck-waterways, truck-air, etc.)	Freight shipper/ network planner

Note: [a] disaggregate level, [b] aggregate level

To sum up, Table 5.1 summarizes the two redundancy measures (i.e., route diversity and network spare capacity) by including the evaluation methods, types of freight (i.e., mixed freight or commodity-specific), types of network (i.e., subnetwork or statewide), and the potential users.

5.4   Numerical examples

Three numerical examples are provided to illustrate the features of the proposed network redundancy measures as well as the applicability of the evaluation methodology. Finally, a case study using the truck-rail network in Utah is carried out to demonstrate its applicability in a bimodal freight network.

5.4.1   Example 1: A small network

5.4.1.1 Preliminary

Example 1 uses a simple network as shown in Fig. 5.3 to demonstrate the features

of the proposed network redundancy measures. This network has six nodes, seven highway links (H1-H7), two origins, two destinations, and four O-D pairs. The two origins are the hypothetical inland container terminals (e.g., seaport) and are only connected to the highway network. The government plans to connect the two ports with local rail services to city A (R1) and city B (R2) in the future. The freight demands of O-D pairs (1, 3), (1, 4), (2, 3) and (2, 4) are 2.5, 1, 1, and 3 in the unit of 1,000 twenty-foot equivalent unit (TEU)/day, respectively. We use the following standard BPR (Bureau of Public Road)-type link performance function:

$$t_a\left(v_a\right)=t_a^0\left[1+\alpha\left(v_a/C_a\right)^\beta\right] \tag{5.27}$$

where t_a^0 is the free-flow travel time on link a; α and β are parameters of the BPR function: $\alpha=0.15$ and $\beta=4.0$. The free-flow travel time in unit of hours and capacity of the seven links in unit of 1,000 TEU/day are also shown in Fig. 5.3.

The constant Ψ_{rs} is set to 1.00 for O-D pairs (1, 3) and (1, 4), implying truck is the preferred mode choice in this example. We assume there are sufficient resources and facilities at the origins and destinations to load and unload the containers during the normal operation hours (i.e., 10 hours/day).

5.4.1.2 *Effects of network reconfigurations*

We consider the following five scenarios of network reconfiguration or enhancement.

Base case : the current highway network

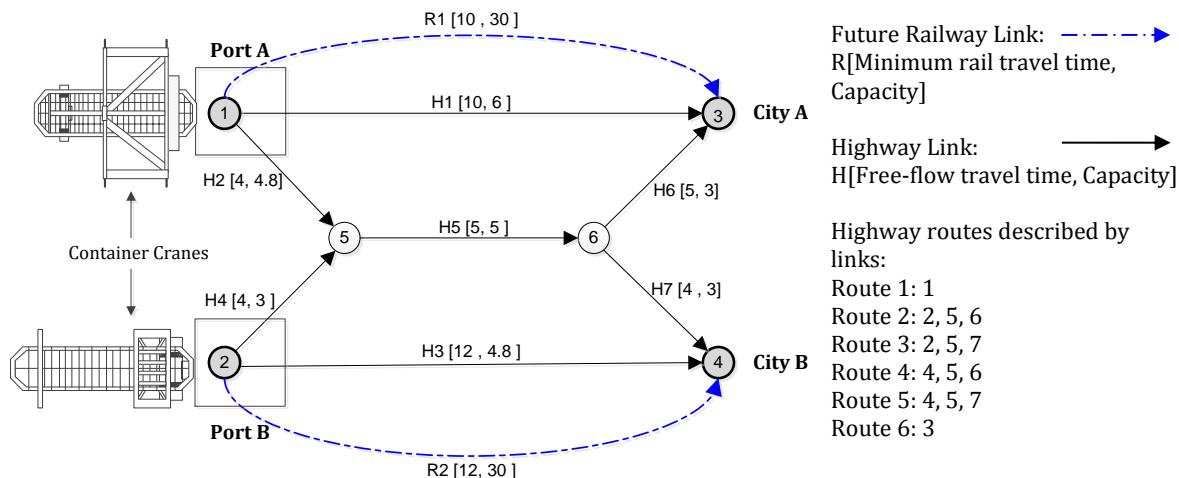Scenario 1 : construct two new roads connecting port A and port B (t_a^0=6, C_a=5)

Fig. 5.3 A small example network

5.4.1.3

Scenario 2 : expand the capacity of link 5 by 50%

Scenario 3 : construct a new road from port A to node 6 (t_a^0=6, C_a=8)

Scenario 4 : construct a new road from port B to node 6 (t_a^0=6, C_a=8)

Scenario 5 : Base case + railroad from port A to city A (t_a^0=10, C_a=30) and railroad

from port B to city B (t_a^0=12, C_a=30)

The purpose of Scenario 1 is to enhance the connections between the two origins

by constructing a highway connecting the two ports. From a pure network topological

viewpoint, link 5 is a critical link (or potential bottleneck) as it serves all four O-D pairs

and it is part of the only route that serves O-D pairs (1, 4) and (2, 3). Scenario 2 is

designed to expand the capacity of this critical link by 50%. In addition, O-D pairs (1, 3)

and (2, 4) have a large freight demand volume. In order to enhance the route connections,

we construct a new road from Port A to node 6 and from Port B to node 6 in Scenario 3

and Scenario 4, respectively. Furthermore, railroads between O-D pairs (1, 3) and (2, 4)

are introduced in Scenario 5. For simplicity, we enumerate all simple routes rather than determining the efficient routes in this example.

First, we examine how route diversity and network spare capacity complement each other for network redundancy characterization. The number of routes of the four O-D pairs and the network capacity multiplier under the above six scenarios are shown in Table 5.2. From these results, the following observations can be drawn:

♦ By comparing Scenario 1 with the base case, we can see the degree of connections of O-D pairs (1, 3) and (2, 4) is increased from 2 to 3 and from 1 to 3 for O-D pairs (1, 4) and (2, 3). The degree of connections at the zonal levels (i.e., origin and destination) also increases from the average of 1.73 to 3.00. However, the network capacity multiplier for this scenario is the same as in the base case. This is because the capacity constraint on link H3 is active in the base case, and remains active in Scenario 1 despite new routes were added; thus, the network capacity multiplier cannot be further increased. On the other hand, the comparison between Scenario 2 and the base case indicates that expanding the 'critical' link capacity can only increase the network spare capacity while keeping the number of routes intact. In addition, Scenario 3 increases both route diversity and network spare capacity simultaneously. Hence, under different network reconfigurations or enhancement schemes, using either route diversity or network spare capacity solely may not be able to fully measure the network redundancy. However, they can complement each other using a two-dimensional network redundancy characterization.

From a pure network topology standpoint, Scenario 3 and Scenario 4 have a symmetric effect on network redundancy. This is also witnessed by the improvement of

route diversity. However, they have significantly different network spare capacity values. Scenario 3 increases the network spare capacity compared to the base case; whereas Scenario 4 shows that constructing a new road from Port B to node 6 will make the network overloaded by 25% of the existing O-D demand **q**. This is because adding a new link in Scenario 4 will create a shortcut route (i.e., route with nodes 2, 6 and 4) that diverts traffic from route 6 (i.e., H3) to this new route. This traffic shift can overwhelm link H7 which has less capacity. This comparison also shows the importance of 'integrating' route diversity and network spare capacity in order to avoid a biased network redundancy assessment. In addition, from Scenario 4, there exists a trade-off between route diversity and network spare capacity. Adding a new road may not always increase the network-wide spare capacity. Thus, we need to optimize them simultaneously (as a bi-objective problem) in order to design an optimal redundant network.

♦ We further explore the features of route diversity. Note that the basic definition of route diversity is at an O-D pair level, measuring the degree of connections for a specific O-D pair. However, we can aggregate it to different levels according to the evaluation purposes. Recall that Scenario 3 and Scenario 4 have a symmetric degree of connections. However, the degrees of connections at the zonal and network levels are different as indicated in Table 5.2. Particularly, the numbers of routes to destination 3 and destination 4 are the same (i.e., 4) in both scenarios, whereas the aggregate degrees of connections to these two destinations are quite different. The reason is that the aggregation explicitly considers the effect of freight demand on route diversity. Typically, the more freight carriers within an O-D pair, the more available routes are needed to accommodate

Table 5.2: Network redundancy measures under different scenarios

Scenario	Number of routes				Degree of connections at the zonal level (O-origin, D-destination)				Degree of connections at the network level	Maximum allowable freight flows (x1000 TEU/day)	Network spare capacity (multiplier)
	O-D (1,3)	O-D (1,4)	O-D (2,3)	O-D (2,4)	O-1	O-2	D-3	D-4			
Base Case	2	1	1	2	1.71	1.75	1.75	1.75	1.73	13.40	1.787
1	*3*	*3*	*3*	*3*	*3.00*	*3.00*	*3.00*	*3.00*	*3.00*	*13.42*	*1.787*
2	2	1	1	2	1.71	1.75	1.71	1.75	1.73	13.93	1.856
3	3	2	1	2	2.71	1.75	2.43	2.00	2.20	13.90	**1.864**
4	2	1	2	3	1.71	2.75	2.00	2.50	2.26	5.65	**0.750**
5a	3*	1	1	3*	2.43	2.50	2.43	2.50	2.47	16.04	2.139
5b	3*	1	1	3*	2.43	2.50	2.43	2.50	2.47	19.52	2.606

Note:* include one railway route

a: multimodal reserve capacity, b: multimodal ultimate capacity

the freight demands. In addition, we can see constructing a new road from node 1 to node 6 in Scenario 3 (from node 2 to node 6 in Scenario 4) is quite beneficial for the connections of origin 1 and destination 3 (origin 2 and destination 4). Hence, the degree of connections at the network level is also increased in Scenario 3 and Scenario 4.

♦ The construction of a new railroad in Scenario 5 increases both route diversity and network spare capacity. As can be seen, the degree of connections increases for all zones. Two approaches for assessing network spare capacity are considered: reserve capacity model for Scenario 5a and ultimate network capacity model for Scenario 5b. Note that the multiplier in the ultimate network capacity model ($\hat{\mu}$) is computed by

$$\hat{\mu} = \sum_{rs} q_{rs}^{total,\max} / \sum_{rs} q_{rs}^{total,base\_case}$$. Scenario 5a indicates that the multimodal system can

accommodate additional 2,620 TEU/day or about 20% of the current demand pattern. However, if the variation in the demand pattern is allowed, the network can additionally sustain 6,120 TEU/day or about 45% of the current demand volume. The multipliers in the reserve capacity in Scenario 5a and in the ultimate capacity in Scenario 5b are 2.139 and 2.606, respectively. These results indicate that the future network with rail services can significantly increase the network spare capacity to accommodate a substantial increase in the container traffic.

5.4.1.4 *Effects of capacity degradation*

Next, we examine the redundancy of a disrupted system. Disruption on the highway links caused by disasters can degrade the capacity of freight transportation network. At this point, some interesting scenarios from the above analysis are examined (i.e., Scenarios 3, 4 and 5). The effect of such a disruption is modeled by gradually

reducing the capacity of link 5 (i.e., the critical link) to 85%, which will result in a bottleneck in the network. Fig. 5.4 compares the capacity multipliers of the base case, Scenario 3 (i.e., adding a link between Port A and node 6), and Scenario 4 (i.e., adding a link between Port B and node 6). It can be seen that the additional link in Scenario 4 will make the system worse because the network is overloaded by 25% at the initial stage as mentioned in the previous section. On the other hand, the additional link in Scenario 3 can enhance the re-routing capabilities to sustain additional container flows without overloading the network, which in turn improves the network redundancy compared to the base case.

Furthermore, the capacities of multimodal networks are analyzed in Fig. 5.5. As expected, the railroad can enhance the network redundancy as more freight flows are distributed to the rail mode. However, depending on the severity of capacity degradation, the capabilities of alternative mode could be reduced (i.e., when the capacity reduction of link 5 reaches 40%). This is because the primary network that contains the bottleneck does not have sufficient residual capacity to accommodate such a demand pattern. In the case of the ultimate network capacity model, we can see that more containers can be accommodated during the degradation. This is because we allow spatial deviations of demand volumes to be added to the routes and modes that still have spare capacity. In essence, the strategies to enhance the network redundancy should focus on providing adequate capacity to accommodate changes in traffic demand.
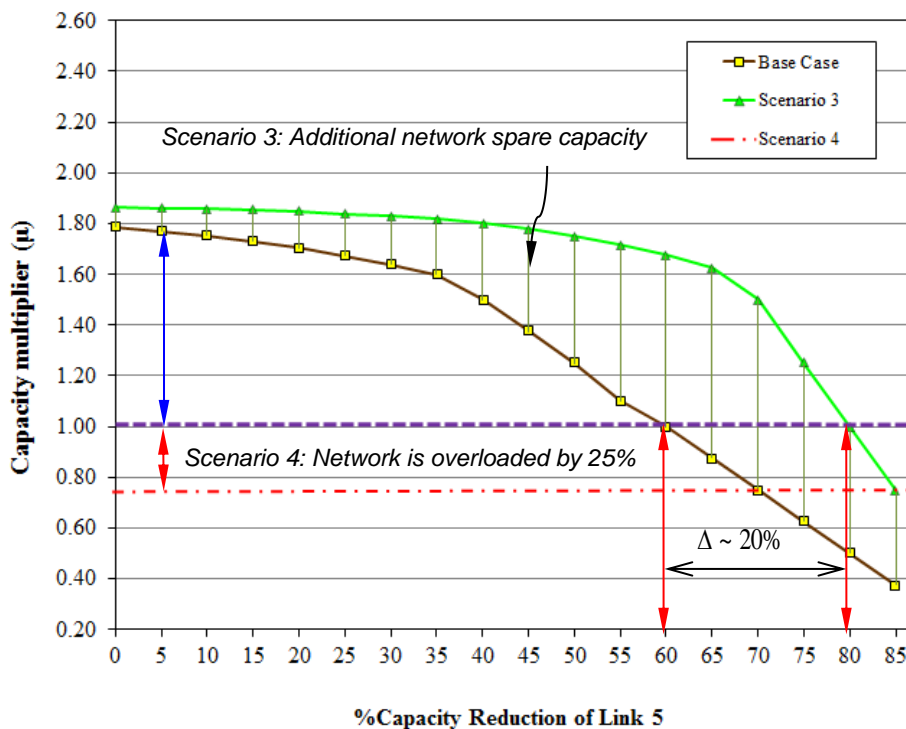
Fig. 5.4 Network spare capacities with different road network reconfigurations
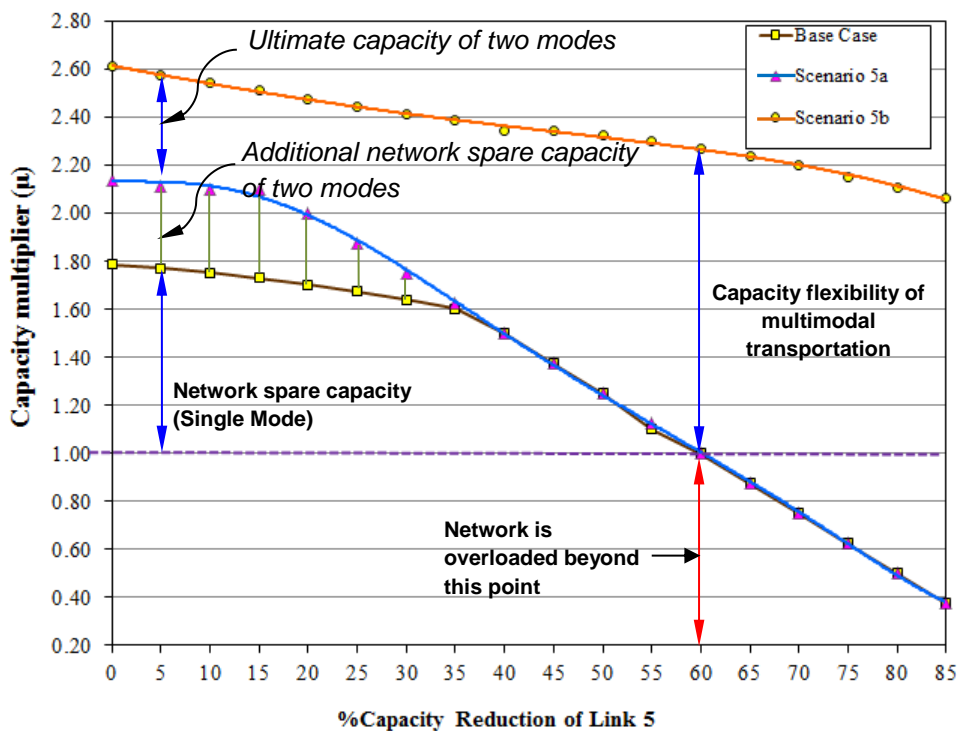

Fig. 5.5 Network spare capacities of multimodal freight network

5.4.2   Example 2: Utah statewide freight highway transportation network

In this example, we focus on the application of assessing the redundancy of truck freight movements on the Utah statewide highway network.

5.4.2.1 <u>Freight transportation network and demand</u>

According to the FAF database (Federal Highway Administration (FHWA), 2007), truck is the dominant mode of freight transportation as it shares approximately two-thirds (i.e., 65%) of all freight transported in Utah. In this example, therefore, we assess the redundancy of the statewide highway network based on the mixing freight demands that are transported by truck. For the freight transportation network in Utah, we used the Freight Analysis Framework (FAF) network. It was originally extracted from the National Highway Planning Network (NHPN). Fig. 5.6 depicts the Utah statewide freight transportation network. The study area consists of 29 counties and 19 external stations (i.e., entry and exit points around the state borders). The highlighted area, the Wasatch Front Regional Council (WFRC), consists of three major counties: Salt Lake, Weber and Davis counties. The major freight activities in Utah are mainly generated from the WFRC area. The network has all major roads in the state including interstate freeways, US routes, state routes, and connector roads. Local streets are not included in this network. In Utah, the interstate freeways, I-15, I-70, I-80, and I-84 are the major truck routes and can be seen as the major backbones. As can be seen, the most important interstate for truck traffic is I-15. The centroid connectors for each county in Utah were pre-specified by FAF. The network consists of 385 nodes, 944 links, and 2,256 O-D pairs.

Link capacity was estimated based on the maximum number of vehicles a lane can accommodate in an hour classified by facility types. They were generated from the

2002 Highway Performance Monitoring System (HPMS) capacity procedure (FHWA, 2002). Note that freight demand derived from the FAF database was based on the annual average daily truck traffic (AADTT) O-D matrices, so link capacity values were required to replicate the daily equivalent capacity for a given link. To do so, we adopted the daily capacity conversion factors based on the roadway classifications used in the Utah Statewide Travel Model (USTM) conducted by Utah Department of Transportation (UDOT)'s consultant team (i.e., Wilbur Smith Associates in cooperation with Resource Systems Group, Inc., 2009). The capacity was then expanded by dividing the hourly capacity with the conversion factors and used for subsequent traffic assignment analysis. The passenger car equivalent (PCE) factors for multi-unit and single-unit trucks were also adopted from the USTM.

The truck O-D trip table is a required input for the assessment of network redundancy. We developed a simplified method to estimate a statewide truck O-D trip table using the FAF commodity database. The FAF commodity database is publicly accessible from the Freight Management and Operations Database from the FHWA. Using a sub-area analysis in transportation planning software, the flows entering and leaving Utah were captured for truck movements and estimated as four matrices including truck flows within Utah (Internal-Internal, I-I), from Utah to other states (Internal-External, I-E), from other states to Utah (External-Internal, E-I), and through truck flows (External-External, E-E). Truck flows were then converted to truck trips using the truck payload equivalent factor (TPEF) derived from the Federal Vehicle Inventory and User Survey (VIUS) database.
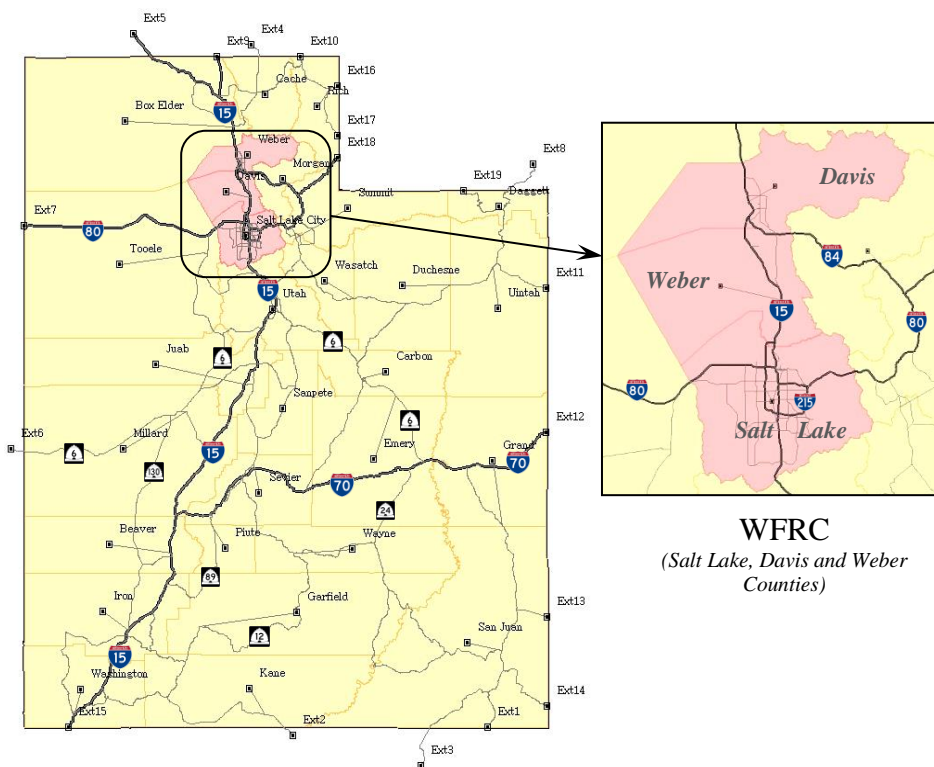
Fig. 5.6 Utah statewide freight transportation network

The passenger flows were proportionally estimated from the USTM and preloaded to the highway network in order to represent the congestion as a combination of passenger and truck traffic volumes. The passenger car equivalent (PCE) factors for trucks were also estimated from the USTM. Please refer to the USTM report by Wilbur Smith Associates in cooperation with Resource Systems Group (2009).

5.4.2.2 *Evaluating the current network's redundancy*

Dimension 1: We evaluate the number of efficient routes to quantify the degree of connections between each O-D pair. The total number of efficient routes for all 2,256 O-D pairs is 18,390 routes with an average number of 8.15 routes per O-D pair. To demonstrate the degree of connections at the zonal level, we aggregate the number of

efficient routes at an O-D level to the origin, destination, and network levels. a and b depict the route diversity dimension for counties and external stations in Utah at the origin and destination levels. The arrows in the figures represent the entering and exiting freight flows at major external stations along the interstate freeways. The average number of efficient routes at the zonal level is 383 routes per zone. As can be seen, the number of efficient routes for many counties is very low. About 21 out of 29 counties (e.g., Iron, Beaver, Millard, Juab, etc.) in Utah have a lower number of efficient routes than the statewide average. With a lower level of route diversity, these counties tend to be more vulnerable to network disruptions, and potentially may result in isolation from the highway system if the critical links on these limited routes are disconnected.

In addition, we can observe that the route diversity measures at the origin and destination levels are quite different. From a pure network topological viewpoint, this reveals an asymmetric effect on route diversity. Using Salt Lake County as an example, the degree of connections at the destination level is significantly higher than that at the origin level, indicating there are more opportunities for truck traffic that are traveling from other origins to Salt Lake County to reroute in the event of a disruption. The route diversity for external stations (represented by the size of circles) for both origin and destination levels are similar (i.e., no asymmetric effect), while the external stations connected to the interstate freeways (e.g., external station 15 on I-15, external station 12 on I-70, external stations 7 and 18 on I-80) exhibit a higher level of route diversity. Next, we investigate the effect of truck demands by measuring the demand-weighted route diversity.
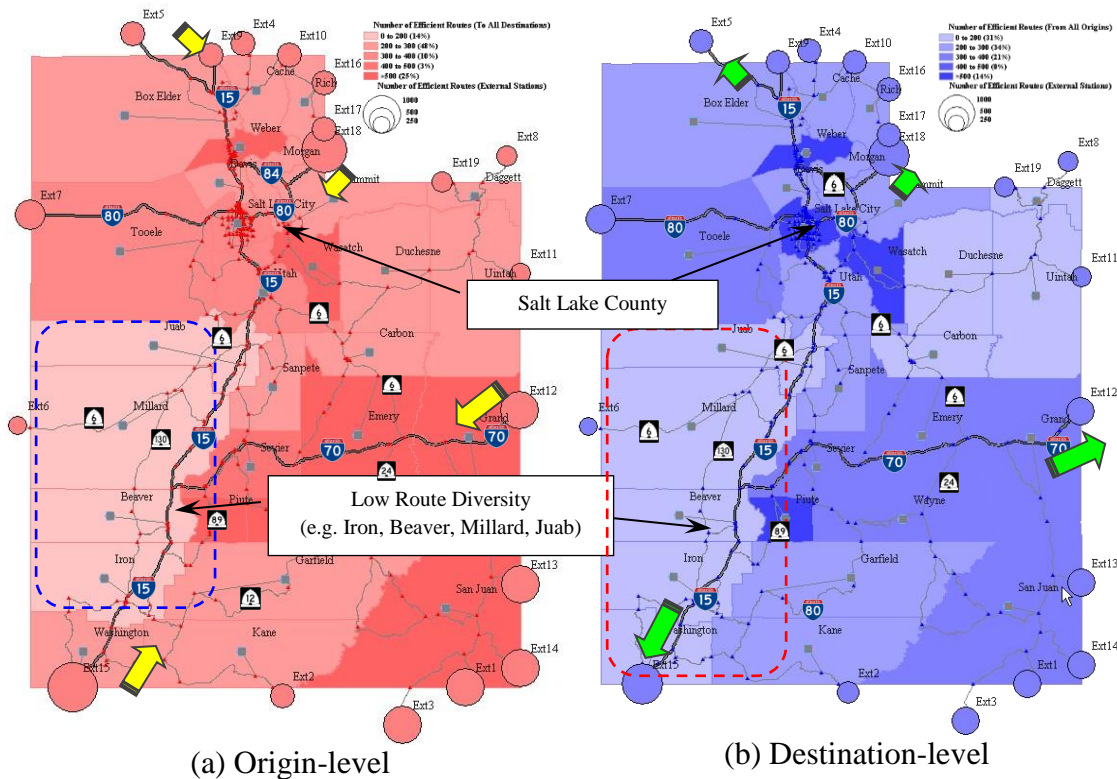
Fig. 5.7 Route diversity for counties/external stations in Utah

Fig. 5.8a and Fig. 5.8b depict the demand-weighted route diversity measures at the origin and destination levels by explicitly considering the effect of truck demands on route diversity. Typically, more truck traffics within an O-D pair need more available routes to disperse the truck demands. A higher degree of route diversity would be beneficial for origins and destinations with high freight demands or activities in the urban areas (i.e., locations where warehousing and distribution centers are located). Truck demands in these urban areas account for a significant share of the total truck traffics in Utah.
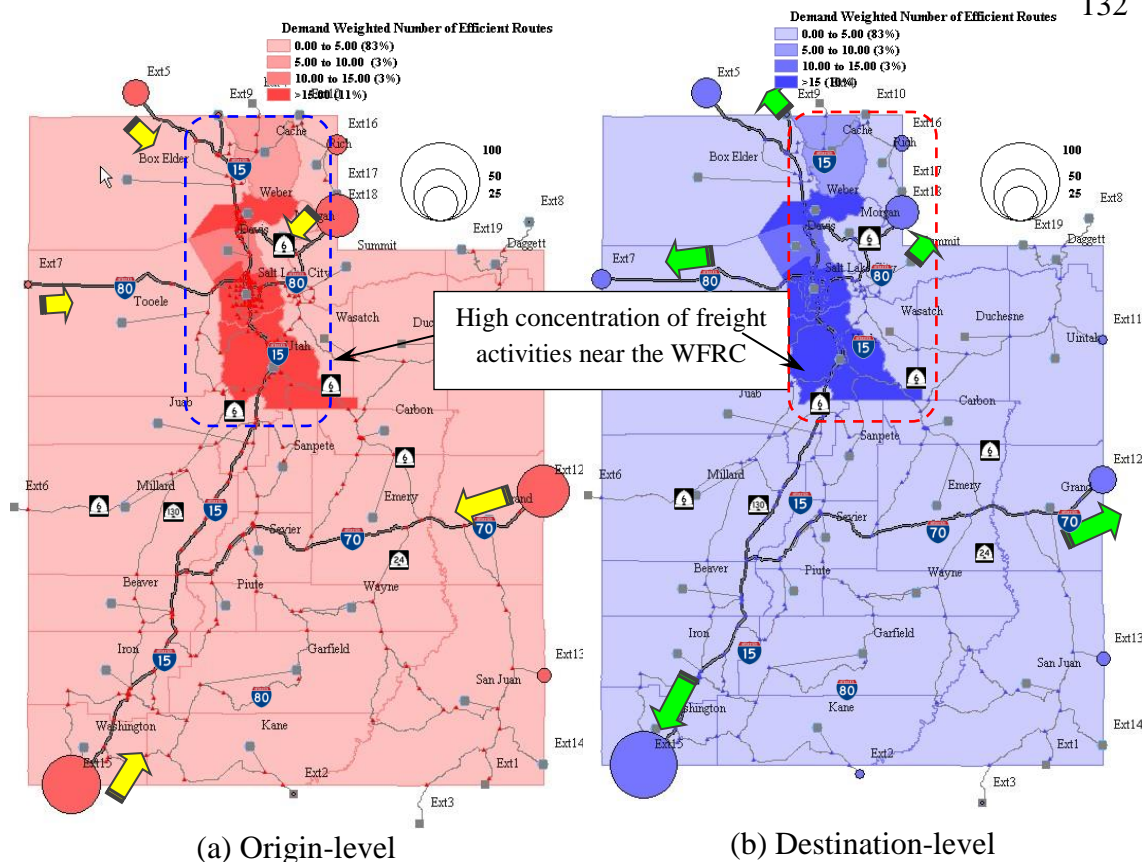
(a) Origin-level   (b) Destination-level

Fig. 5.8 Demand-weighted route diversity for counties/external stations in Utah

The results in Fig. 5.8 show the counties around the WFRC area (e.g., Salt Lake, Weber, Davis, and Utah counties) have a significantly higher demand-weighted route diversity compared to other counties. Likewise, the demand-weighted route diversity values for the external stations connecting to the interstate routes are also high, especially for external station 15. The average network levels of demand-weighted route diversity by origins and by destinations are 451 and 1063 routes per zone, which are quite different from the average of 383 routes per zone from a pure network topological viewpoint. Hence, ignoring the effect of truck demands may lead to a biased assessment of network-wide degree of connections.

Dimension 2: Fig. 5.9 shows the assigned traffic volume and the volume/capacity (V/C) ratio map under the current traffic condition. As can be seen, with the existing demand pattern, there are many congested locations on the interstate routes, especially the ones on I-15 South near Beaver County and Salt Lake County. According to the Highway Capacity Manual (National Research Council, Transportation Research Board, 2000), the level-of-service (LOS) criteria defined by the V/C ratios are as follows. LOS A: 0~0.26, LOS B: 0.26~0.41, LOS C: 0.41~0.59, LOS D: 0.59~0.81, LOS E: 0.81~1.00, and LOS F: >1.00. The link V/C ratio distribution under μ=0.70 to 1.50 is shown in Fig. 5.9.
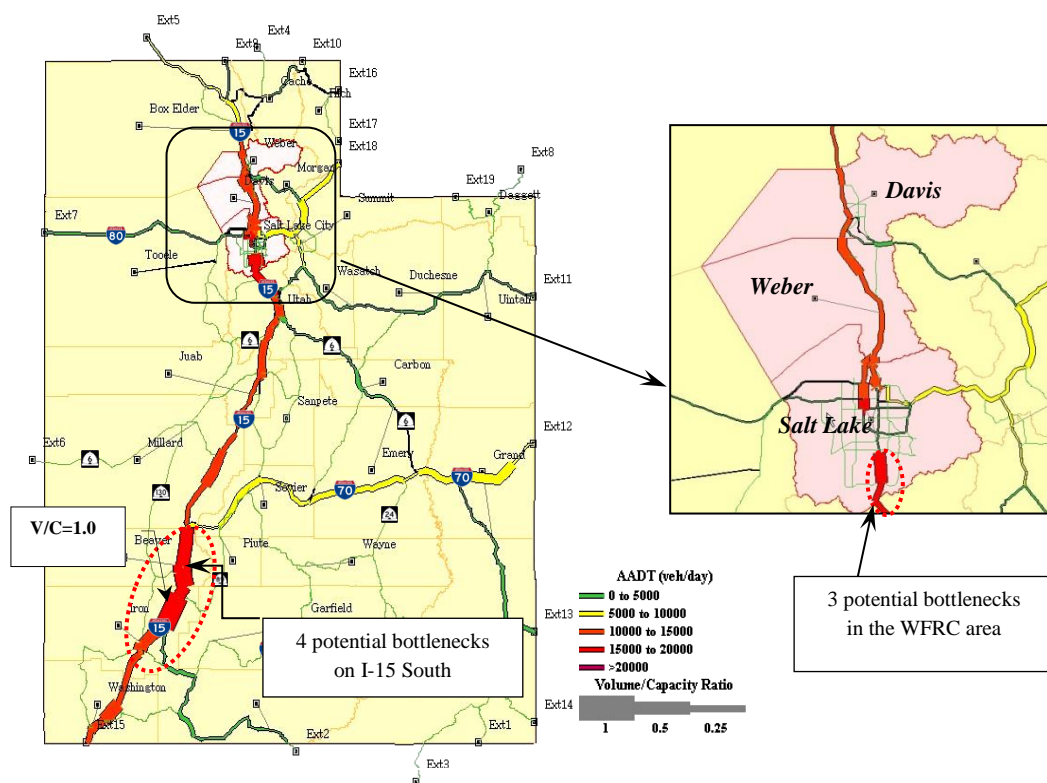

Fig. 5.9 Freight traffic volume and V/C ratio map (current condition, μ=1.00)

The network capacity multiplier μ is 0.717, indicating that the current network is overloaded by 28% of the existing O-D demand **q**. This means the current network has insufficient capacity to accommodate the existing demand under the pre-specified LOS requirement (i.e., LOS E or V/C≤1.00). We further allow V/C>1.00 in order to evaluate the relationship between demand multipliers and network congestions of future scenarios. As expected, the V/C ratio in many locations increases with the demand multiplier. For example, there are about 30 links (about 4% of links in the network) at LOS D, E, and F based on the current demand. These links can be considered as the potential bottlenecks in the future that prevent the network from realizing a higher capacity. The number of potential bottlenecks gradually increases from 5% to 10% of the total network links when μ increases by 50% (i.e., from 1.00 to 1.50). To accommodate the current demand, we
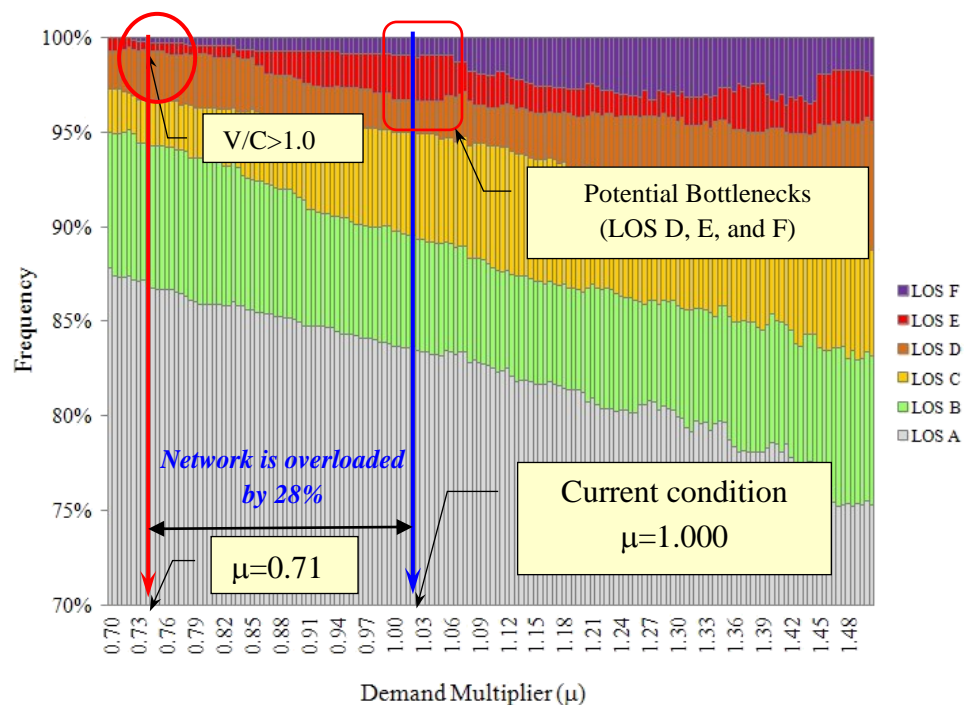
Fig. 5.10 Link V/C ratio distribution and LOS

need to improve the network by expanding existing roads, constructing new roads, or both.

5.4.3   Example 3: Utah coal transportation networks

In this example, we apply the redundancy measures to assess the truck-rail network in Utah as a case study to demonstrate its applicability in a bimodal freight network. A majority of coal (about 95%) produced in Utah was consumed within the state mainly for electricity generation. Coals are transported from the coal mines in Emery County to the unloading facilities which are operated by different private companies such as Union Pacific (UP) railroad's facility near Levan, BNSF Railway interchanges at Provo and Grand Junction, Colorado. According to the recent FAF database in 2007, about 55% and 45% of coals are transported by railroads and by trucks, respectively. Fig. 5.11 shows the schematic network diagram of coal transportation in Utah. In this simplified bimodal network, we can see that some coal mines (e.g., mine group 2 and mine group 3) have access to loading facilities: Wildcat and Savage coal terminals through branch lines, and directly connect to the main railroads to the Provo station (i.e., node 6). Note that according to the coal mine guideline by BNSF Railway, Provo station is the railway interchange for coal trains in Utah and it has the facility to unload coal and rail yard to accommodate coal traffic. However, some other coal mines, such as Southern Utah Fuel Company (SUFCO) (i.e., mine group 1) which is one of the most productive coal mines in Utah, do not have any railroad access. Coals from these mines have to be transported to the UP connection at Levan (i.e., node 5) by trucks.
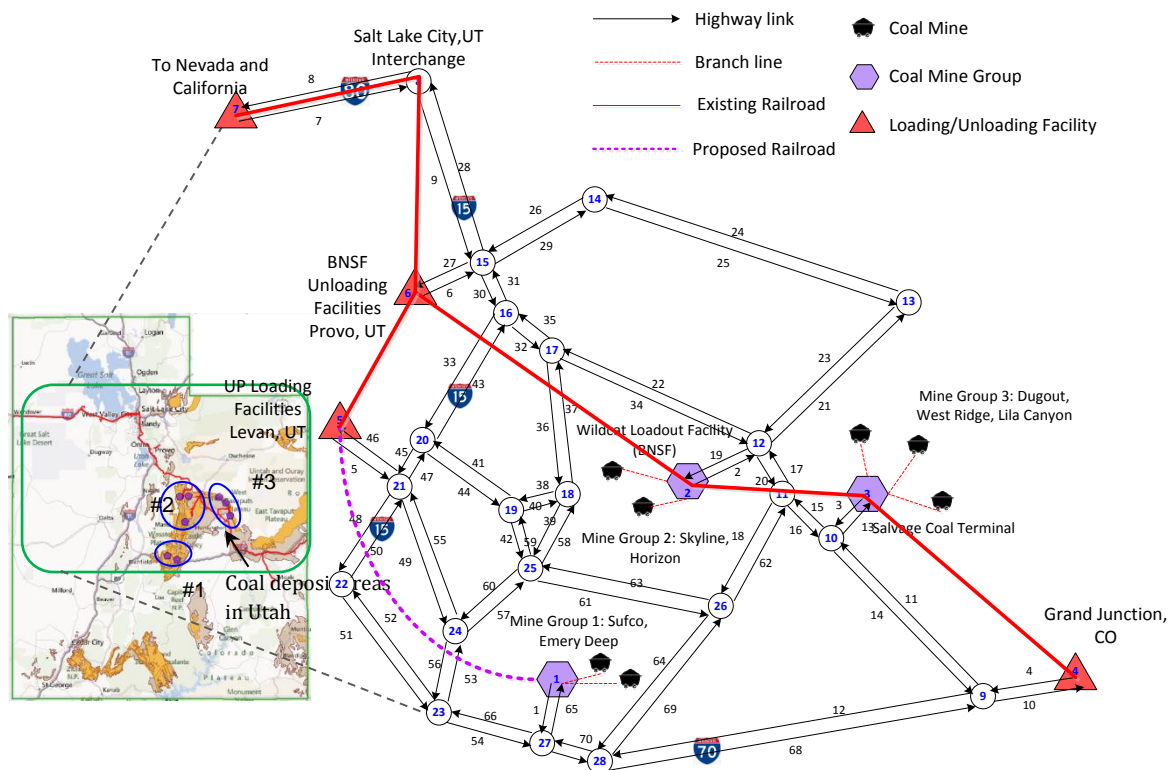
Fig. 5.11 Coal transportation network and loading and unloading facilities in Utah

However, there is a project proposed by the Six County Association of Government (SCAOG, 2004) to build a 43-mile railroad connecting coal mine group 1, particularly serving the coal operations of SUFCO to the UP facility. This case study will assess the proposed project in terms of the route diversity as well as the spare capacity of the bimodal network.

The coal transportation networks consist of six major railroad corridors and 70 highway links extracted from the FAF network as shown in Example 2. The highway links consist of both interstates and state routes. The major interstate routes for coal transportation are I-15 and I-70. The coal O-D demands from different mine groups are

derived based on the FAF database. Note that the FAF database provides the annual commodity flow for within, to, and from Utah.

The annual demands are disaggregated and proportionally distributed from each mine groups to different loading facilities using information from the coal production (Vanden Berg, 2010). The railway capacity is estimated based on the number of tracks, speed (here we use 35 miles/hour), and length. The average delay per train at capacity (A_c) is estimated for these corridors based on Eqs. (14)-(16). Note that we adopt the typical number of cars or wagons per train for bulk from the study by Association of American Railroads (2007) (i.e., 112 wagons per train and 110 tons /wagon). For simplicity, we also assume the rail tracks are on flat terrain. Further, we compute the residual capacity of highway links that are used by the background passengers and other commodity types of truck traffics. In Utah, coal is hauled from the mine sites to the rail loading points by trucks with an average payload of 43 tons/truck (Union Pacific, 2013). For simplicity, we adopt this empirical payload factor to convert the residual highway capacity to residual tonnage for coal traffic, so that all variables are expressed in the same unit (i.e., KTon/day). Table 5.3 summarizes the O-D demands and Table 5.4 summarizes the capacity of railroads, respectively. The efficient truck routes and the railroads from the three coal mine groups are depicted in Fig. 5.12a, Fig. 5.12b and Fig. 5.12c. Particularly, there are totally seven efficient routes from mine group 1, whereas only four efficient routes from mine groups 2 and 3. As can be seen, there are several simple routes connecting these coal mines to the destinations but only few of them are efficient routes.

Recall that the efficient routes only include links that are further away from the origin and/or closer to the destination. The results indicate that the Utah coal

Table 5.3 Coal O-D demand (KTon/day)

Coal O-D Demand (KTon/day)	Grand Junction (Node 4)	Levan (Node 5)	Provo (Node 6)	Nevada/California (Node 7)
Mine Group 1 (Node 1)	0.00	25.87	0.00	0.00
Mine Group 2 (Node 2)	0.00	0.00	19.13	7.47
Mine Group 3 (Node 3)	3.54	0.00	17.66	6.90

Note: *300 working days/year*

Table 5.4 Practical maximum train capacity (single track, 35 mph.) (KTon/day)

Corridor Capacity (KTon/day)	Grand Junction (Node 4)	Levan (Node 5)	Provo (Node 6)	Nevada/ California (Node 7)
Mine Group 1 (Node 1)	0.00	**(185.00)***	0.00	0.00
Mine Group 2 (Node 2)	54.11	0.00	142.56	45.58
Mine Group 3 (Node 3)	56.38	0.00	136.41	45.58

Note: **capacity of the proposed railroad*

network has limited efficient routes and less diverse. Fig. 5.12a shows the efficient routes from mine group 1, which mostly consist of links on I-15 and I-70.

Coal truck traffic from this mine group, therefore, has to heavily rely on the interstate freeways. A backup route consisting of links on the state routes (e.g., link 53 and link 55) could be used when the primary route is not available, but they may have insufficient capacity to accommodate the future demands as they are potential bottlenecks as shown in Fig. 5.12d. It is important to note that these efficient routes are even more critical if they contain the bottlenecks or critical links as they will be easily overwhelmed by truck traffic, and thus adversely degrade the network capacity and its serviceability overall.
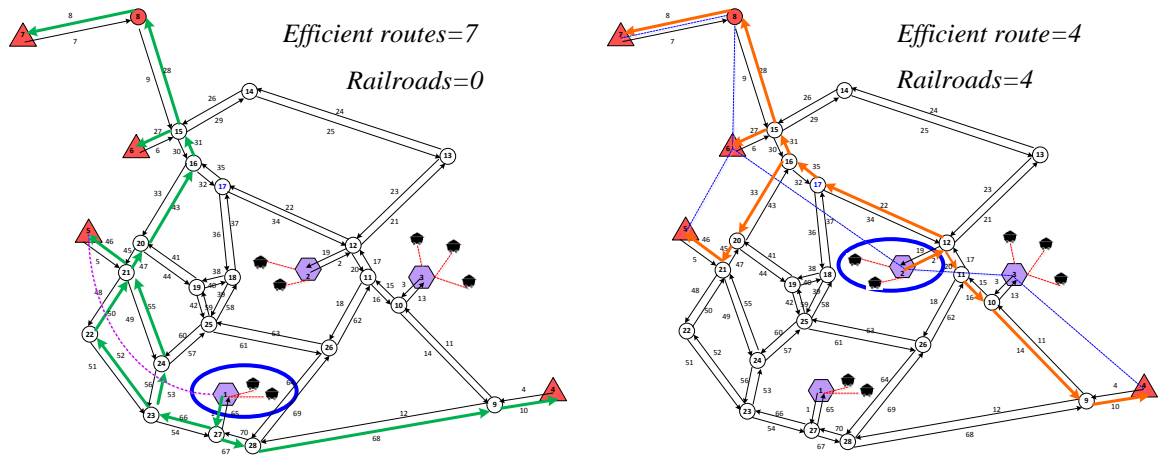
a) Efficient routes from mine group 1

b) Efficient routes from mine group 2
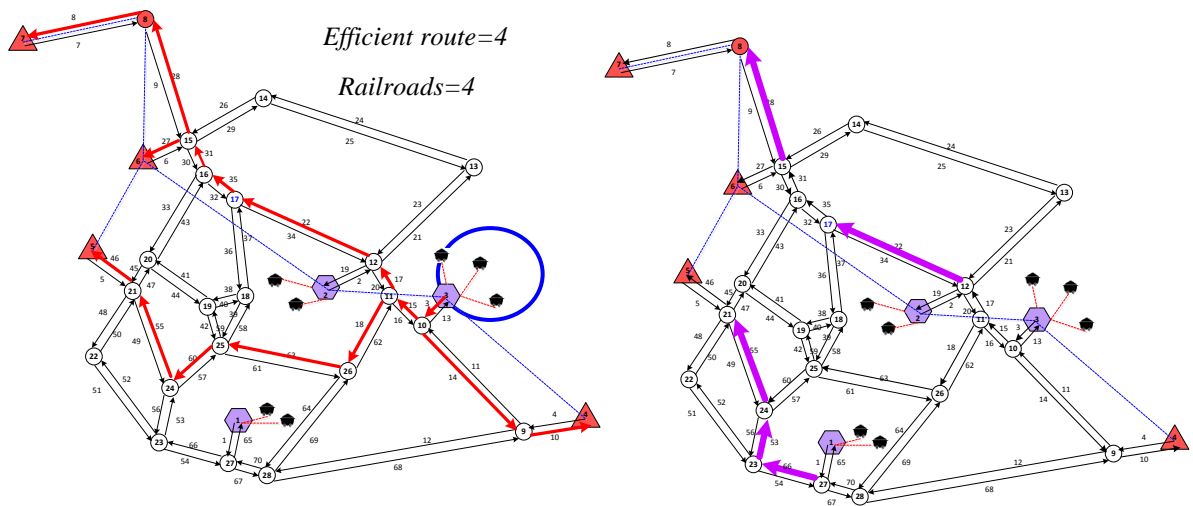
c) Efficient routes from mine group 3

d) Potential bottlenecks (top 5 links)

Fig. 5.12 Efficient routes from three mine groups and potential bottlenecks

The redundancy-oriented network design that explicitly accounts for the capacity of the efficient routes should be considered in the future research.

From the topological viewpoint, the proposed railroads can enhance the interconnectivity between the mine and destinations, and hence the bimodal route

diversity. Fig. 5.12b and Fig. 5.12c show that there is only one efficient route per O-D pair from mine groups 2 and 3; however, there is at least another railroad connecting these mines to the loading facilities. These efficient routes are the major routes for coal mine groups 2 and 3, and at the same time they are viewed as the backup routes when the railroad services are not available. Again, the bottlenecks can occur on the state routes (e.g., link 22) connecting from these mine groups, which could eventually reduce the overall network capacity.

The network spare capacity measured based on two types of network capacity models (i.e., reserve capacity and ultimate capacity) are also implemented. The results of the current bimodal network and the bimodal network with the proposed railroad are illustrated in Fig. 5.13a and Fig. 5.13b. From the results, some observations can be drawn. First, the current network of coal transportation still has some reserve capacity as the network can accommodate an additional 73% of the existing demand (i.e., $\mu=1.73$). It indicates the new railroads can provide not only the more efficient way to transport coal from mine group 1 but also can enhance the network-wide spare capacity, hence can help reduce congestion in the highway network. The differences in O-D distribution from the reserve capacity model are less than those from the ultimate capacity model, because the reserve capacity model implicitly assumes the existing demand pattern to be uniformly scaled by a common multiplier (i.e., the existing demand pattern has to be preserved). The amount of network capacity (i.e., 421.4 KTons/day) from the ultimate capacity model is significantly higher than that from the reserve capacity model (i.e., 146.0 KTons/day), as it allows the spatial deviations in demand volumes to different routes and modes.

Current Multimodal Networks · *Multimodal Networks with Proposed Railroad*

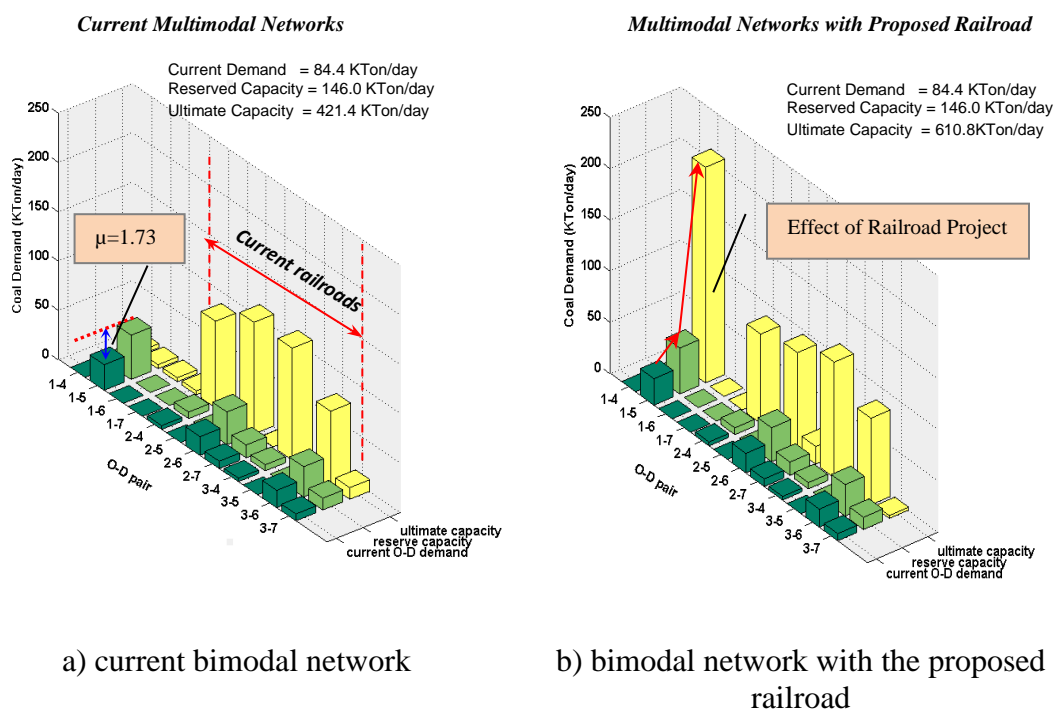a) current bimodal network · b) bimodal network with the proposed railroad

Fig. 5.13 Maximum O-D demand, network spare capacity for the current bimodal network and network with the proposed railroad

However, the additional demand volumes are concentrated on the mine groups 2 and 3 as they directly receive the benefit of the railroad. In addition, we can observe less additional demand volumes from mine group 1 (i.e., node 1). The main reason is that the additional truck traffic from this mine can quickly overload the highway network and then reduce the overall network capacity. This also implies the limited redundancy for this particular origin. The network capacity is significantly improved when the new railroad is built for O-D pair (1, 5). This is expected because the demands have shifted from truck to rail transportation and eventually the total network capacity can increase to 610.8 KTons/day. The new railroad could be used as a core route which will enhance both diversity and spare capacity of the coal transportation in Utah.

5.5   Conclusions

In this research, we proposed a two-dimensional approach for characterizing the redundancy of freight transportation networks: route diversity and network spare capacity. Specifically, the route diversity dimension evaluates the existence of multiple efficient routes available for freight users or the degree of connections between an O-D pair. The network spare capacity dimension quantifies the network-wide spare capacity with an explicit consideration of congestion effect. Note that the network capacity is the maximum throughput under a pre-specified LOS requirement. The network spare capacity measure employs an optimization-based approach to explicitly determine the maximum throughput while considering both congestion effect and route choice behavior. The reserve capacity model implicitly assumes the existing demand pattern to be uniformly scaled by a common multiplier. Though the results of this approach are useful in determining the possible ranges of demand that can be accommodated, yet it underestimates the network-wide capacity due to the requirement of preserving the fixed O-D demand pattern. This study further relaxed this assumption by allowing the variation of O-D demand by modes to determine the ultimate capacity of multimodal networks.

Three numerical examples were also provided to demonstrate the features of the two redundancy measures as well as the applicability of the evaluation methodology. The analysis results of the hypothetical network revealed that the two measures have different characterizations on network redundancy from different perspectives, and they can complement each other by providing meaningful information to both freight carriers and network planners. The multimodal network can increase the diversity of freight transportation system and it can serve as a redundant component when the primary mode

is inoperative. In addition, the multimodal network can enhance the redundancy of freight network as the system can gain additional benefits from the joint-use capacity derived from the effects of modal shifts.

The network redundancy assessment also focuses on evaluating freight bottlenecks, which are important according to their congestion impacts on the U.S. highway system. The state-specific commodity flows within, out of, into and through Utah were extracted from the freight analysis framework (FAF) database and then converted into truck trips to generate a truck origin-destination (O-D) trip table. Results of the case study in Utah statewide freight transportation network indicated that many counties in Utah have a low level of route diversity, especially for the counties in rural areas. The disruption of potential bottlenecks, especially along the interstate route or primary truck route, would significantly reduce the network redundancy as those counties have less route diversity to divert traffic as well as less spare capacity to accommodate freight demands. The application of the proposed measures for assessing the redundancy of coal multimodal networks is also promising. The results highlight the significant improvement of network redundancy (in terms of both route diversity and network spare capacity) when the proposed railroad project is introduced to the network.

The basic idea and approach presented in this research could be used to deal with the vulnerability issues arising in freight transportation networks. The measures could be useful in supporting the strategies for the infrastructure management and investment decisions, which can improve the resiliency of freight transportation system. The directions for future research include: developing more advanced network capacity models that can capture the multidimensional choices in freight networks (e.g., travel,

destination, mode and route choices), investigating the characteristics and operations of

freight distribution at nodes (e.g., drayage, yard, warehouses, etc.) in the multimodal

network in terms of their supporting role to enhance the system capacity and redundancy.

Addressing these issues will contribute to resilient freight transportation and logistic

systems.

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CHAPTER 6

CONCLUDING REMARKS

6.1   Conclusions

The primary objective of this study was to develop a quantitative framework for assessing vulnerability and redundancy of freight transportation networks. The major contributions arising from this dissertation are threefold. First, we developed a two-stage approach for estimating a statewide truck O-D trip table and demonstrate how this technique can be applied to estimate truck flows on statewide truck routes and corridors. Truck O-D trip table is frequently used for supporting numerous statewide freight planning activities. This study employed a statewide truck O-D trip table for the vulnerability and redundancy analyses. Second, we developed a spatial decision support system (DSS) tool for freight transportation network vulnerability analysis. The spatial DSS tool was created to enhance the ability in assessing vulnerability as well as managing the consequences due to disruptions. Third, we proposed a methodology for evaluating redundancy of freight transportation networks. The proposed measures were applied to assess the redundancy of a statewide highway network and a multimodal coal transportation network in Utah. The key findings and conclusions of each chapter are summarized as follows:

Chapter 2 reviewed the literature on freight transportation network modeling, methods to estimate truck O-D trip table, vulnerability and redundancy analyses.   The limitation of the traditional approaches to estimate truck O-D trip table, vulnerability and redundancy analyses were also discussed.

Chapter 3 provided a two-stage approach for estimating a statewide truck O-D trip

table. The main contributions of this chapter were as follows. The two-stage approach has the capability in filling the modeling gap and drawbacks of the commodity-based and trip-based models in estimating a truck O-D trip table. The PFE model further allows great flexibility of incorporating data at different spatial levels to makes use of various existing field data and commodity-based data with commercial and empty truck trips for estimating truck O-D trip tables. A case study was conducted using the Utah statewide transportation network to demonstrate the applicability of the proposed approach in a real-world setting. Using the proposed method, a truck corridor analysis was conducted to determine the congested links and potential bottlenecks in the Utah statewide network.

Chapter 4 developed an approach to assess vulnerability of freight transportation network using two quantitative measures: Origin-Destination (O-D) connectivity and freight flow pattern change. This research have developed a DSS tool and demonstrated how this tool can be used to support decision making in case of network disruptions. A "*what-if*" analysis approach by generating the disruption scenarios of the structurally deficient bridges in or near the high seismic hazard areas in Utah were assessed. Some strategic planning implications for preparedness and devising remedial strategies to protect the transportation network derived from the case studies were also discussed in this chapter.

Chapter 5 proposed an approach for assessing the redundancy of freight transportation networks. Redundancy is characterized by two main dimensions: route diversity and network spare capacity. The route diversity dimension is to evaluate the existence of multiple efficient routes available for freight users or the degree of connections between a specific O-D pair. The network spare capacity dimension is used

to quantify the network-wide spare capacity of multimodal freight transportation networks with an explicit consideration of congestion effect. The network spare capacity models consist of the reserve capacity model and ultimate capacity model. Both models employed a bi-level optimization-based approach to determine the maximum throughput while considering both congestion effect and travel choice behavior. The results indicated a multimodal transportation network could gain substantial capacity benefits achieved by the *substitution effect* through a modal shift. A hypothetical network was used first to demonstrate the complementary effects of the two main dimensions. Two case studies of the Utah statewide and multimodal coal transportation networks were provided to demonstrate the features of the two-dimensional approach as well as the applicability of the evaluation methodology.

6.2   Discussion on redundancy strategy to reduce vulnerability of freight
        transportation networks

Vulnerability of freight transportation networks in this dissertation focused on the problem of reduced O-D connectivity caused by the disruption of freight chokepoints on the truck routes in the statewide network. The reduced O-D connectivity can have strong impacts on the continuity of freight services and additional transportation costs explicitly derived from detours and delays of freight traffic. Because the *just-in-time* environment is crucial in modern business, the disruption of freight network can easily create a ripple effect throughout the supply chain. From a transportation planner's viewpoint, network redundancy is one of the *supply-side* strategies to ensure the service continuity and ability to accommodate the diverted traffics with sufficient network capacity. The basic idea and approach presented in this dissertation could also be used to deal with the connectivity

and capacity issues arising in the degradable freight transportation networks. In this sense, redundancy can be increased by either increasing the number of routes or by increasing the amount of capacity on a certain link/route for a certain mode of transportation, hence ultimately reduce potential vulnerability in freight transportation networks. Another important observation we recognized during the course of these studies is that the concepts of vulnerability and redundancy are inversely related and are often seen as opposite ends on a continuum. However, the specific nature of the relation is unknown, yet it is interesting to investigate the reciprocity in future research.

Beside the concept of redundancy, the other end of vulnerability would be other system performance's supportive measures such as resiliency: resourcefulness, recovery, and robustness (Bruneau *et al*., 2003), and reliability (Berdica, 2002). Fig. 6.1 summarizes the major relations among these concepts with a major focus on vulnerability and redundancy as the opposite relations: one attempts to demote the system performance while the other one attempts to elevate it back or resist to the adverse changes whether it is vulnerability or other possible threats such as incidents and severe congestions. The interaction between *demand* and *supply* also plays an important role in the evaluation of vulnerability in a freight transportation system as they are interconnected, yet are very fragile during such situations. The aforementioned factors could perturb or impact this interaction and deteriorate the overall system performance.

Thus, public agencies in charge of freight transportation networks and infrastructure planning could benefit from the proposed framework in using a computerized decision support system tool to illustrate the negative consequences and assess the capability of freight transportation system in terms of route diversity and
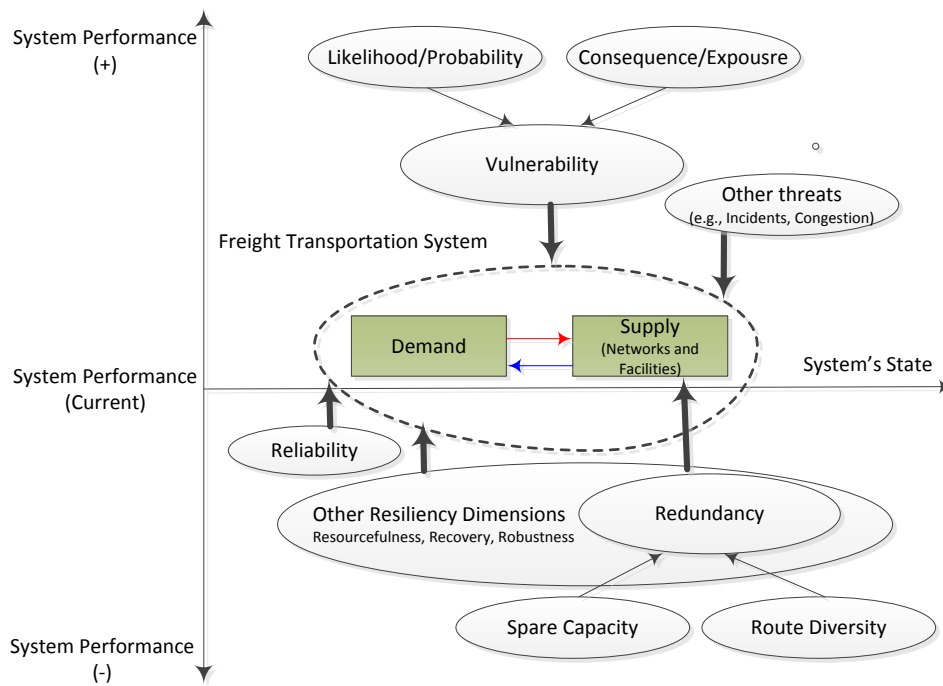
Fig. 6.1 A diagrammatic summary of the conceptual relations among vulnerability, redundancy, and other supportive and unsupportive measures.

network spare capacity to accommodate and manage the current and future transportation network vulnerability.

6.3   Future research directions

To advance the proposed models and methods developed in this dissertation for freight transportation networks, potential recommendations for future research include the following:

6.3.1   *Improvement and extension of PFE*

In Chapter 3, the PFE model has been constructed solely based on a single vehicle class. Further work is necessary to develop a PFE model to account for multiclass and, multimode (e.g., commercial, single-, multiple-unit trucks, and passenger cars) (see, for

example, Yang and Huang, 2004; Marcotte and Wynter, 2004; Wong *et al*., 2005), so that it can better reflect the actual congestion of the statewide highway network. Although the results using Utah as a case study are satisfactory, accurate and consistent truck counts are required in the PFE to produce reliable results. Extending the PFE to handle inconsistent traffic counts at the statewide level should be explored (see, for example, Chen *et al*., 2009; Chen *et al*., 2010).   In addition, constraints such as trip length frequency distribution could be incorporated to model different types of statewide truck traffics (i.e., short haul, long hual, and empty truck trips) in PFE.

6.3.2   Improvement of statewide freight transportation data

The truck surveys at freight companies and distribution centers for each county and state border (e.g., Weigh-in-motion (WIM), Port of Entry (POE) stations) should be conducted to understand the freight movements in the statewide network. The current truck O-D trip table is estimated from the commodity flow data from FAF and truck counts collected by the UDOT. It should be updated using the newly developed Utah Statewide Travel Model (USTM) to improve the accuracy and quality of the truck O-D trip table.

6.3.3   Decision support system tool enhancement

The decision support system tool should be upgraded to the core engine of DotSpatial (Dotspatial, 2013), a newly developed GIS library, to take advantage of the latest developments in spatial data analysis and mapping functionality. An optimization approach to identify the critical chokepoints, particularly based on the concept of network flow interdiction approaches (e.g., Church *et al*., 2004; Murray *et al*., 2007) should be integrated in the future DSS tool. Potential applications of the DSS tool include (1)

prioritizing the structurally deficient bridges for maintenance and retrofitting, (2) estimating the economic impacts based on commodity values, (3) integrating the vulnerability analysis to the statewide planning model.

6.3.4   *Improvement of route diversity measure*

This study proposed to measure route diversity based on the concept of "efficient routes" by Dial (1971). A set of efficient routes can be considered as the *reasonable choices* in our framework. This algorithm has an advantage as path enumeration is not required. However, this algorithm has some known drawbacks as it sometime produces unrealistic flows patterns, as discussed by Akamatsu (1996), in which no flow is assigned on paths that are being used in reality. The route diversity measure should be investigated to address this shortcoming (see, for example, Si *et al*., 2010), and also further consider other associated factors in route choice model such as the effects of congestion, stochasticity, similarity, and overlapping among routes (see, for example, Prashker and Bekhor, 2004; Pravinvongvuth and Chen, 2005; Chen *et al*., 2012).

6.3.5   *Improvement of network spare capacity measure*

Further study should extend the proposed network capacity model to specifically evaluate capacity of the efficient routes as discussed in Chapter 5. The network redundancy index that combines route diversity and network spare capacity by transforming the problem into a new multiple weighted objectives (MWO) should be developed to simultaneously capture both measures at the same time. Furthermore, an advanced network design model should be developed to better allocate the limited resources to enhance the capacity of freight transportation networks (see some examples in other disciplines: Coit and Konak (2006) for multi-objective redundancy allocation

problem in reliability engineering; Kumar *et al*. (2006) for optimal design of redundant water distribution networks, Okasha and Frangopol (2010) for establishing lifetime redundancy design of highway bridges, Randles *et al*. (2011) for distributing redundancy and robustness in cloud computing system, and so on).

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Peer-reviewed Conference Papers & Presentations

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