Infrastructure Management
Project A: Developing a Framework for Prioritizing Infrastructure Improvements on Critical Freight Corridors
and
Project B: Developing a Market-based Framework for Freight Infrastructure Management

Prepared by

The Pennsylvania State University and University of Virginia

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INFRASTRUCTURE MANAGEMENT

PROJECT A: DEVELOPING A FRAMEWORK FOR PRIORITIZING INFRASTRUCTURE IMPROVEMENTS ON CRITICAL FREIGHT CORRIDORS

PROJECT B: DEVELOPING A MARKET BASED FRAMEWORK FOR FREIGHT INFRASTRUCTURE MANAGEMENT

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16. Abstract Fully operational highways are necessary for efficient freight movements by the trucking industry. Yet, the combination of limited funding and aging infrastructure creates a grim scenario for states, which are dependent upon the economic benefits of goods movements. This research develops a comprehensive, freight-based prioritization framework to identify freight infrastructure needs critical to maintaining economic vitality by incorporating economic metrics associated with infrastructure performance and level of service. Framework outputs are a prioritized list of infrastructure needs to sustain economically critical highway infrastructure with consideration to regional economic impacts and safety and mobility improvements. In summary, the framework first evaluates infrastructure needs on a specified highway network, then prioritizes those needs using a decision model to balance developed economic metrics that estimate regional corridor-wide benefits of the local improvement with severity of needs as quantified with conditional performance measures. The developed metrics and prioritization methods are consistently applicable to any region within the United States, and two proofs of concept examine data from the Virginia highway system to demonstrate the methodology.

A review of literature documents existing and proposed highway improvement prioritization frameworks to incorporate best practices into the methodology developed for this research. While the literature discounts use of economic development performance measures and the economic importance of a corridor is typically taken for granted, this research adds the dimension of economic significance of a corridor into the prioritization process for infrastructure improvements to generate motivation for private sector investment. An input-output model is used to identify the most transportation dependent industrial sectors, which are then linked with commodity flows using the Federal Highway Administration's Freight Analysis Framework. A set of conditional performance measures are selected to identify critical locations meriting improvements, including National Bridge Investment Analysis System (NBIAS) outputs, International Roughness Index (IRI), truck fatality crash rate and truck crash rate, and deficiencies in geometric standards. The prioritization methodology is demonstrated by applying the three developed economic metrics to two proofs of concept in Virginia: the U.S. 460 expressway between Petersburg and Hampton Roads and the U.S. 29 bypass in Charlottesville.

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ABSTRACT

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INTRODUCTION

Highways are essential for efficient freight movements and economic activity. In 2007, trucks hauled 40% of freight ton-miles in the United States, while their market share continued to grow (BTS, 2011). Further, freight ton-miles carried on highways increased 31% between 1997 and 2007, bolstering the reliance of commerce on and necessity for efficient, uncongested highways (BTS, 2011). Yet, the state of transportation infrastructure in the United States has reached a critical point such that closures and congestion cause an immeasurable adverse effect on already suffering regional and national economies.

Bridge and pavement degradation occurs even faster than expected since freight tonnage on the highways has become much higher than was originally planned and continues to increase (ASCE, 2009). When the interstate system was constructed, beginning in the late 1950s, bridges were typically designed for a fifty-year lifespan; today, the average age of a bridge is 43 years old (AASHTO, 2008). According to the American Society of Civil Engineers (2009), 26% of bridges in the United States are classified as either structurally deficient or functionally obsolete. With so many bridges in need of replacement, the cost of a new bridge so high, and inherent limitations with bridge inspections, unexpected closures or bridge failures are inevitable, such as that on I-35W in Minneapolis in 2007.

Such a road closure would be more economically detrimental to certain highways, depending on variables such as the number of trucks impacted, the commodities transported on that highway, additional delays, and adverse affects on alternate routes. While research has been conducted on infrastructure asset management (Cambridge Systematics et al., 2009; Dicdican et al., 2004; Shufon et al., 2003), often an inherent importance of a highway is assumed by its classification, e.g., interstate, national highway, etc., with minimal guidance to identify the most significant corridors. Further, there are no universal metrics to accurately describe the economic significance of a corridor or the magnitude and range of economic impacts by transportation investments (Peters et al., 2008; Meyer, 2001).

Moreover, despite the dominance of trucking in commerce and the economy, planning for freight is still an emerging area, even though truck-related issues represent a major part of what transportation planning attempts to address (Rodrigue et al., 2009). Numerous tools and guidelines are available to assist freight analysis, including the Federal Highway Administration's (FHWA) Freight Analysis Framework (FAF) (FHWA, 2010-a) to estimate and project freight flows between states and regions. Further, several states have performed studies on freight and infrastructure including the Virginia Department of Transportation's (VDOT) "Virginia Statewide Multimodal Freight Study" (Cambridge Systematics, 2009-b; Cambridge Systematics, 2010) and Ohio Department of Transportation's, "Freight Impacts on Ohio's Roadway System" (2002). However, the minority of states that actually utilize freight performance measures use only a handful of disparate metrics, most of which are not even used to calibrate performance of specific state programs (Gordon Proctor & Associates, 2011).

Simply having a freight-based infrastructure prioritization framework in place may help departments of transportation (DOTs) secure funding for projects from public and private sectors. It has been shown that having an asset management plan in place can help secure funds from legislatures (Cambridge Systematics & Meyer, 2007).

In spite of the current trend for tolling roadways to make up for funding shortfalls from the fuel tax, the trucking industry has indicated a passionate opposition to toll roads, with over half of truckers surveyed in one study citing a willingness to travel far distances out of the way to avoid tolls (Wood, 2011). However, this study also indicated trucking sector acceptance of tolling for new capacity, and a large need for better communicating the benefits of a facility for increased acceptance (Wood, 2011). With a freight-based infrastructure prioritization methodology in place to guide DOT investments to needs critical to goods movements, the trucking industry also may be more inclined to contribute funds through innovative payment strategies.

Finally, current gas tax revenues no longer provide sufficient funds for infrastructure needs. The state of Oregon has a pilot program to investigate the implementation of a VMT-fee to replace the gas tax. Increasingly, new highway projects are funded through alternate mechanisms such as public-private partnerships and/or tolling. Regardless, an imbalance often remains between the user cost and the infrastructure damage sustained from fully loaded freight vehicles on the highways.

PROBLEM STATEMENT

The combination of limited funding and aging infrastructure creates a grim scenario for states, which are even more dependent upon the economic benefits of freight movements in the current suffering economy. Economic metrics of highway infrastructure needs are required for a comprehensive, freight-based prioritization methodology to ultimately be integrated into strategic statewide and metropolitan planning organization (MPO) planning to identify and guide funds to infrastructure and operations improvements on critical corridors with regard to regional economic impacts, and structural, safety and mobility improvements. Prioritizing freight needs in this way may generate financial support from the private sector to promote their interests, while at the same time focused funds to specific freight corridors may draw truck traffic, easing truck-induced degradation on parallel highways.

PURPOSE AND SCOPE

The purpose of this research is to develop economic metrics and funding framework to assist with prioritization and funding of infrastructure needs on critical freight corridors to maintain economic vitality. This research can inform a variety of stakeholders and decision-makers to make sustainable, informed decisions to support freight and economic activity, and is intended to be used as a tool to help leverage funding from the private sector based on derived benefits for projects not yet able to be subsidized by the public sector. This research builds on existing asset management strategies, identifying, prioritizing, and identifying funding for specific infrastructure needs on highways based on freight-based factors, such as the structural rating, economic importance, safety, and mobility. Developed economic metrics identify corridors most critical to freight transport, quantifying potential corridor-wide benefits to be gained by investing in specific infrastructure needs. The developed metrics and prioritization methods will be consistently applicable to any region within the United States, and proofs of concept examine data from the Virginia freight network to demonstrate the developed methods.

METHODOLOGY

This project is organized into two integral parts to organize the collaborative work between researchers from the Pennsylvania State University and the University of Virginia. Projects A and B proceeded concurrently and are linked by the primary categorical prioritization areas of infrastructure needs and their lifecycle costs as they translate to costs associated with local and regional economic impacts, environmental, energy and sustainability impacts, and safety and mobility costs. Fee mechanisms, taxes and other revenue generating mechanisms and associated institutional structures for varying funding arrangements (Project B) are be linked to the performance measures developed to prioritize infrastructure investments (Project A).

Project A Methodology: A Framework for Prioritizing Infrastructure Improvements

The following tasks fulfill the study objectives:

1. *Conduct review of literature.* Literature is examined on infrastructure needs identification and prioritization techniques and guidelines. A review of literature found numerous studies for asset management, but less work that helps to quantify the economic importance, based on freight movements, of aging bridges and pavements to the freight network for repair or replacement prioritization. The state of practice for prioritizing infrastructure needs in the United States and internationally is documented. Sources for the literature review include, but are not limited to, the Virginia Center for Transportation Innovation and Research Library, Transport Research International Documentation, Worldcat, TLcat, and University of Virginia Engineering Library databases.

2. *Investigate freight-specific performance measures to identify infrastructure needs.* Based on the literature review and current DOT state of practice, a set of performance measures reflecting freight-based needs such as the structural soundness of bridges and pavements are identified, as well as measures to consider truck safety and mobility. Typical measures considered include truck speed, bridge load rating and deficiency rating, international roughness index (IRI) and present serviceability rating (PSR) pavement scores, and truck crashes.

3. *Investigate strategies to measure economic importance.* Economic importance of the freight network is established using the input-output model that identifies industrial sectors that are most dependent upon the transportation network. The flows of these sectors is linked to commodities in the FHWA's FAF, providing tonnage of these

flows between and within selected regions. An origin-destination model is incorporated to disaggregate these interregional flows to the existing network, given by the FAF. This prioritizes infrastructure needs by weighting the importance of corridors, specifically identifying those most critical to freight movements. Other economic metrics, specifically excess trucking costs derived from mobility and safety data are developed. Given the industries impacted based on the commodities on specific links, another economic metric is generated by inputting these excess trucking costs to the input-output model. These metrics are designed for private sector interests, quantifying potential benefits resulting from specific infrastructure investments.

4. *Link economic importance and freight infrastructure needs.* The use of VDOT's Asset Management System and Statewide Planning System are investigated to assist with infrastructure needs identification based on freight-based structural soundness, safety, and mobility performance measures selected in step 2. Economic metrics developed in step 3 can be applied to prioritize the needs. A decision model is developed to balance economic priorities with the relative severity of safety, mobility, and structural needs, which can be translated into excess trucking costs. The output is a list of infrastructure needs for a specified highway network listing current excess trucking costs, projected regional economic benefits, and the prioritized ranking. The relationship between the required inputs and generated outputs of data to execute the prioritization methodology model are illustrated in Figure 1, while the individual steps necessary to run the proposed prioritization methodology model are illustrated in Figure 2.

5. *Conduct proofs of concept.* To demonstrate the model developed in step 4, data from the Virginia freight network is used, although measured economic benefits extend to out-of-state freight stakeholders as well. Prioritization of infrastructure needs for selected corridors is made, that include economic costs associated with safety and mobility issues. Selected corridors will be U.S. 460 and U.S. 29 for which corridor studies have been conducted that can be used in this research for validation purposes. Specifically, proposed projects on these corridors: a limited-access highway for U.S. 460 and a Charlottesville bypass for U.S. 29 north, are evaluated for their economic benefits along the corridors. Both of these projects provide benefits to other routes from which traffic may be diverted by creating a cost savings for trucks, providing indirect economic benefits locally. Further, this research examines whether the proposed projects on these corridors have the potential to enhance economic development opportunities along the corridors due to improved access to markets; the corridor study areas extend beyond immediate the local improvement areas to include benefits to out-of-state markets.

6. *Draw conclusions and recommendations.* Based on proof of concept results and analysis, conclusions and recommendations are provided for successful implementation of this research.

Figure 1. Flow of Inputs and Outputs of Proposed Methodology

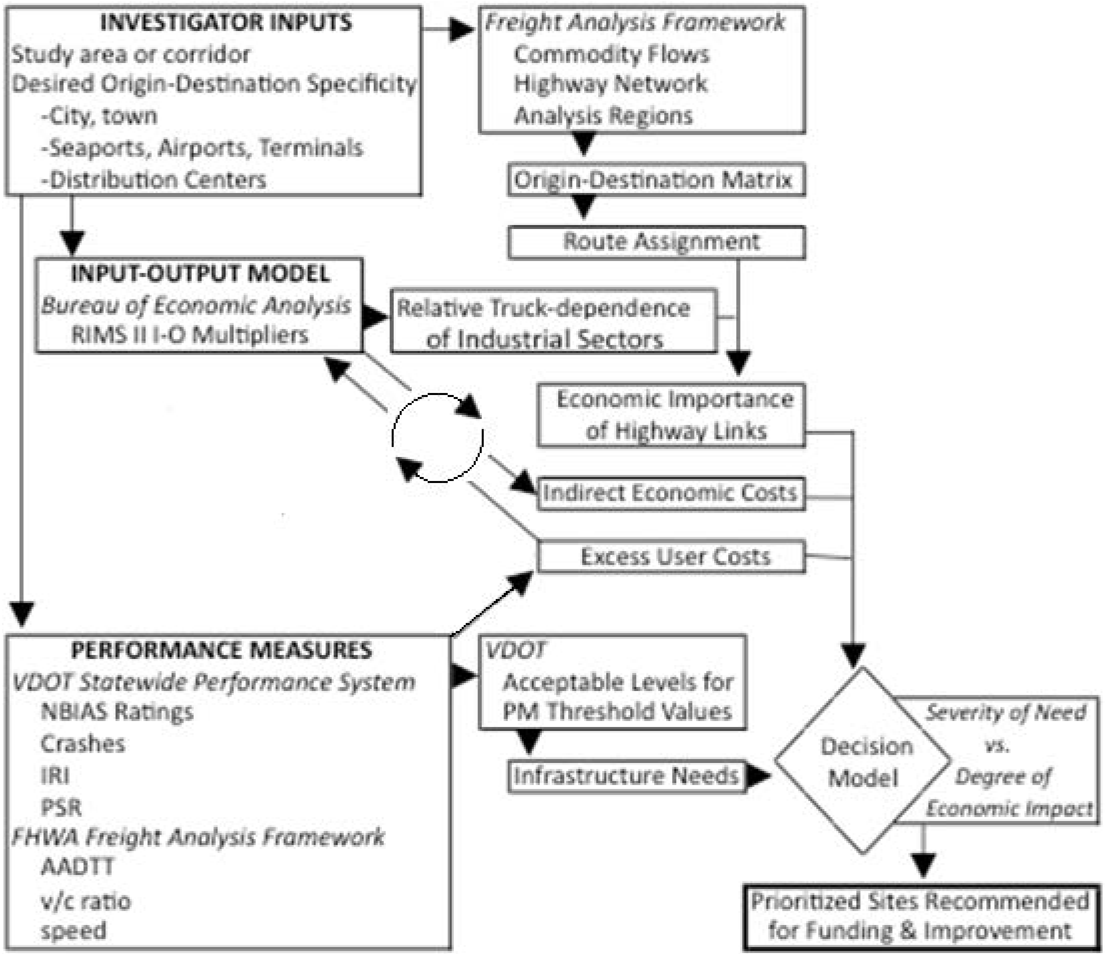
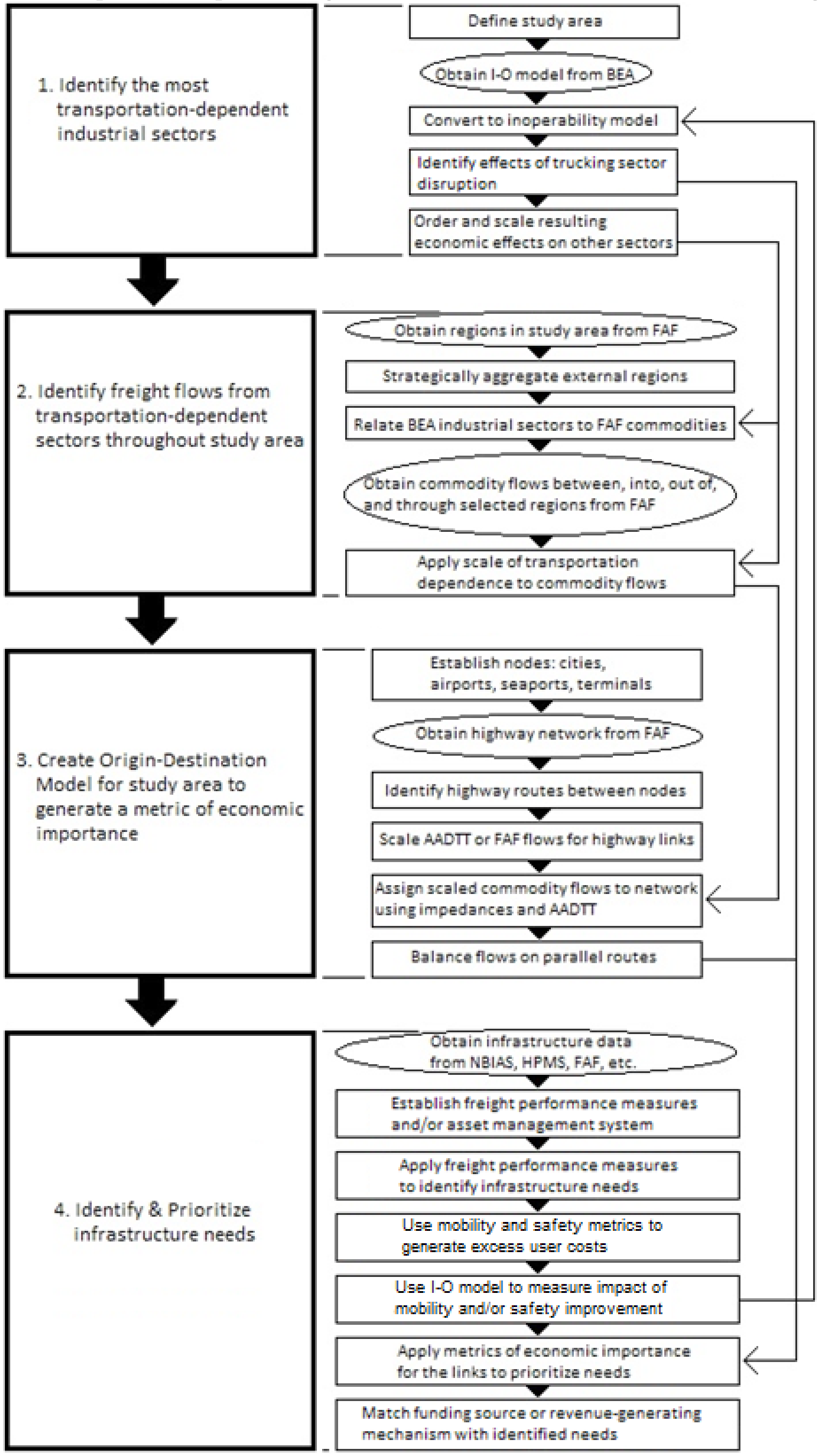


Figure 2. Proposed setup for Freight Infrastructure Prioritization Methodology



7. *Prepare final report.* This final report is prepared to clearly outline the developed prioritization methodology and document the findings of the study. This document can assist stakeholders to make sustainable, informed decisions to support freight and economic activity, and help leverage funding from the private sector based on derived benefits for projects not yet able to be subsidized by the public sector. This tool is intended to help with difficult decisions during times of shrinking budgets and increasing costs to insure the preservation of infrastructure vital to freight flows and economic prosperity.

Project B Methodology: A Market-Based Framework for Infrastructure Management

1. *Conduct literature review*. We focus on the literature in shale gas infrastructure and road network infrastructure. A comprehensive review will be conducted on (i) management of shale gas infrastructure; (ii) shale gas production planning; (iii) urban road traffic management; (iv) city logistics; and (v) market mechanism design and auctions. The literature review will also examine current methods used at state and federal levels to assess freight needs. Resources for this literature review will include, but not be limited to the Virginia Transportation Research Council Library, TRIS, Worldcat, TLcat, and University of Virginia Engineering Library databases.

2. *Shale gas infrastructure and production planning.* The rich resource of Marcellus gas has recently boosted up the interest of people as the drilling technology advances. Apart from the difficulties in exploration and drilling for natural gas, problems of building and developing network that delivers the gas to customers remain unsolved for shale gas companies and government. In this task, we consider an in-land shale gas infrastructure and production planning problem. Multiple gas fields with uncertain reserves are considered in the model. Platforms are connected by pipelines, which will eventually transport the gas to a central pipeline that delivers gas to merchants and customers. The goal is to obtain the maximum expected net present value of the project within a given time horizon. As the revelation of field reserves will affect the decision maker's action, stochastic model with endogenous uncertainties is built. Modern stochastic programming technique is applied. Specifically, a conservative approximation is obtained under the assumption of piecewise constant binary and linear real-valued decision rules.

3. *Urban freight transportation planning.* In this task, we propose a dynamic Stackelberg game-theoretic model for urban freight transportation planning which is able to characterize the interaction between freight and personal transportation in an urban area. The problem is formulated as a bi-level dynamic mathematical program with equilibrium constraints (MPEC) which belongs to a class of computationally challenging problems. The lower level is dynamic user equilibrium (DUE) with inhomogeneous traffic that characterizes traffic assignment of personal transportation given the schedule of freight transportation. The upper level is a system optimum (SO) freight transportation planning problem which aims at minimizing the total cost to a truck company. A mathematical program with complementarity constraints

(MPCC) reformulation is derived and a projected gradient algorithm is designed to solve this computationally challenging problem. Numerical experiments are conducted to show that when planning freight transportation the background traffic is non-negligible, even though the amount of trucks compared to other vehicles traveling on the same network is relatively small. What's more, in our proposed bi-level model for urban freight transportation planning, we find a dynamic case of a Braess-like Paradox which can provide managerial insights to a metropolitan planning organization (MPO) in increasing social welfare by restricting freight movement.

4. *Congestion derivatives.* Deterministic congestion pricing has attracted most attentions in the literature. But little attention has been given to pricing under uncertainty, especially for heterogeneous commuters. In this task, we investigate congestion externalities by considering commuters' risk preferences and heterogeneity. In particular, when price involves exogenous uncertainty which is independent of both central authority and individual commuters, we are able to express commuters' departure equilibriums and the total social cost in closed-form in terms of the departure time and uncertainty. Moreover, we find that uncertainty will lead heterogeneous risk-averse commuters not only to avoid traveling at the time when uncertainty level is high, but also to deviate from their optimal departure sequence. Hence, we are able to show that uncertainty can tremendously increase the total social cost. Furthermore, we also prove that both the central planner and the market-base mechanism have the potential to reduce the total social cost and alter commuters' departure behavior. Specifically, we find out that the central planner can always find a class of financial derivatives to induce the socially optimal departure behavior, while the market-based mechanism may do so at specific cases. Finally, numerical formulation and experiments are given to assess the robustness of our results for more general forms of uncertainties and derivatives.

5. *Prepare final report.* One final report will be prepared to clearly document the findings of our study.

PROJECT A: A FRAMEWORK FOR PRIORITIZING INFRASTRUCTURE IMPROVEMENTS

TASK 1 – LITERATURE REVIEW

1.1 Infrastructure Improvement Prioritization State of Practice

Asset management has become a major component of transportation agencies in recent years as increasing need for improvements is met with budget limitations (FHWA, 2008-a). The FHWA (2008-a) defines asset management as: "a business process and a decision-making framework that covers an extended time horizon, draws from economics as well as engineering, and considers a broad range of assets […that…] incorporates the economic assessment of trade-offs among alternative investment options and uses this information to help make cost-effective investment decisions."

Consequently, numerous studies have been performed to guide agencies and document best practices; the FHWA Asset Management website (FHWA, 2008-a) and the American Association of State Highway and Transportation Officials (AASHTO) Transportation Asset Management Today knowledge site (AASHTO, 2010) both serve as forums for contemporary asset management guidance, state of practice, and research, while Varma (2008) lists a comprehensive list of data sources for freight performance measures. Subsequent sections investigate data that is collected annually and available for input to existing infrastructure improvement frameworks.

1.1.1 Collected data

National databases currently contain information from every state on the condition of bridges and highways. The National Bridge Inventory (NBI) is federally mandated to monitor sub-structure, super-structure, deck, channel and channel protection, and culvert conditions for every structure over 20 feet (Cambridge Systematics et al., 2009; FHWA, 1995). For highway conditions, the Highway Performance Monitoring System (HPMS) includes data on highway condition, performance, use, and operating characteristics (FHWA, 2009-b). While certain information is maintained for all public roads, more data is collected for higher functional class roadways (FHWA, 2009-b). Additionally, over 40 states use the Pontis Bridge Management System, which includes NBI plus more detailed data (FHWA, 2008-a).

Other relevant databases exist but do not contain uniformly collected records for the entire country. Pavement management systems, for example, vary by state as there is no standard format (Cambridge Systematics et al., 2009).

Regarding safety data, a number of systems report a variety of information in ways that usually vary by state. There are no standards or consistency between states for reporting data on safety features like lighting, pavement markings or signage (Markow, 2007). One exception is the Fatality Analysis Reporting System (FARS), which documents all fatal crashes nationally, including truck-related crashes (NHTSA, 2010). The University of Michigan Transportation Research Institute (2010) maintains the Trucks Involved in Fatal Accidents (TIFA) database with extensive records dating to 1980 on fatal truck-related crashes nationally. State crash data systems, however, vary by state and are based on police accident reports. The National Accident Sampling System or General Estimates System contains an annual sample of crashes from these State Crash Data Systems, and extrapolates from this sample to estimate total crashes and their severity (Cambridge Systematics et al., 2009). The Highway Safety Information System (HSIS) is used by nine states and has crash records, roadway inventory, and traffic volume data (FHWA, 2010-c). It is used to study current safety issues, direct research efforts and evaluate the effectiveness of countermeasures (Cambridge Systematics et al., 2009). Finally, State Highway Safety Improvement Plans (HSIP) are reported annually to the federal government for the funding of safety-related enforcement and public awareness programs (Cambridge Systematics et al., 2009). These documents assist in identifying trends and safety improvement needs.

Mobility data can be obtained from several sources. The FHWA FAF includes annual average daily traffic (AADT) and annual average daily truck traffic (AADTT), estimated capacity, volume-capacity ratio, speed, and delay information for a large freight highway network for 2007 and 2040 projections (FHWA, 2010-a). In addition, HPMS, Highway Economic Requirements System for States (HERS-ST), American Transportation Research Institute's FPMweb, and DOTs collect mobility measures (Cambridge Systematics et al., 2009; American Transportation Research Institute, 2010).

Environmental concern is a newer area of focus for state DOTs, thus little data is consistently collected and available for monitoring performance (Cambridge Systematics et al., 2009). The level of greenhouse gas (GHG) emissions can be estimated based on average fuel economies from vehicles at given speeds from available data. Additionally, since energy usage is a function of congestion, eliminating bottlenecks would improve mobility, while also reducing fuel consumption and emissions.

Detailed economic data from the private sector is difficult to gather, as it is not readily shared. However, some data sources, such as the United States Census Bureau and Bureau of Commerce have quality economic data on employment and businesses, as well as freight statistics like operation costs, revenue and employment (Cambridge Systematics et al., 2007). The FAF estimates trucking commodity movements and the volume of long-distance trucks for specific highways (2010-a). Also, the Virginia Freight Study highlights "freight-intensive" industry reliance on transportation services and employment in those sectors (Cambridge Systematics, 2009-b).

Freight data can be obtained for the aforementioned categories in general databases including HPMS, FAF and FARS, including truck crash data, truck volumes, and truck fuel economy. The FAF also contains commodity flow information by tonnage and value between 131 traffic analysis zones nationwide (FHWA, 2010-a). Numerous freight studies contribute additional information, also. The estimated costs of freight delays and bottlenecks caused by freeway or signalized intersections or steep grades are presented in a FHWA study (2008-b) and the TTI Urban Mobility Report (Schrank et al., 2010), while a study by ATRI (2010) identified the 100 most congested freight bottlenecks. A study by Hajek and Billing (2002) tracks trends in freight volume, size, weight and truck technology that affect pavement design; generally, policy & law changes have allowed increasing weights and sizes over time, as truck volumes increase. Finally, state-conducted studies, such as the "Virginia Statewide Multimodal Freight Study" (Cambridge Systematics, Inc., 2009-b), document additional information like locations of distribution centers and their square footage, state bottlenecks, key intermodal connectors, truck parking availability at rest areas, truck accident numbers and locations, and current and projected level of service on the highway network. In general, freight data from the private sector are available, but difficult to compile due to costs and confidentially issues arising from the numerous disparate sources that collect and maintain the information (Varma, 2008).

1.1.2 Existing Prioritization Frameworks

The FHWA utilizes the National Bridge Investment Analysis System (NBIAS) to prioritize bridge investments. The NBIAS views all input bridges as equally important, and uses only NBI data to model maintenance, repair, rehabilitation, and functional improvement investment needs, with a modeling approach derived from the Pontis Bridge Management System (Cambridge Systematics et al., 2005; Robert & Gurenich, 2008); specific rules may be applied to measures to set minimum acceptable conditions that would trigger the system to recommend replacement of the bridge (Robert & Gurenich, 2008). The NBIAS then simulates a budget allocation for bridge projects over time to maximize user benefits while minimizing agency costs (Robert & Gurenich, 2008).

The FHWA's Highway Economic Requirements System (HERS) optimizes highway investments based on HPMS travel forecasts, vehicle speeds, crashes, improvement costs, and predicted pavement and capacity deficiencies (Cambridge Systematics et al., 2005; FHWA, 2008-a; USGAO, 2001); a state version of this tool, HERS-ST is also available. Alternate improvements to highway segments are economically compared with a benefit-cost analysis for potential benefits derived from travel time reductions, crash reductions, vehicle operating costs, and agency maintenance, while costs include capital expenditures necessary to construct the improvement (Cambridge Systematics et al., 2005; FHWA, 2008-a; USGAO, 2001). In analysis, candidate projects are identified to correct pavement, width, and/or alignment deficiencies of a highway segment; performance criteria and/or specified funding constraints prioritize the selected candidate projects (Cambridge Systematics et al., 2005).

Further, many state DOTs use their own prioritization frameworks for infrastructure investments. Many of these have been documented through various studies to highlight innovative or best practices (Cambridge Systematics & Meyer, 2007; Guerre et al., 2005; Li et al., 2005; Lownes & Zofka, 2008; Pagano et al., 2005; Richardson et al., 2009; Shufon & Adams, 2003; Stephanos et al., 2002).

Research has documented ways to streamline prioritization for diverse assets. A strategy used by Maryland for pavement project selection first groups similar projects by traffic volume, road type and class, condition, etc. before optimizing to select projects (Stephanos et al., 2002). Conversely, Ontario has found more consistency by combining numerous regional asset management outputs for bridges and pavements, scaling the cost-benefit outputs, and generating various what-if scenarios for an array of funding thresholds (Guerre et al., 2005). The New York State DOT uses trade-off analysis for pavements, bridges, safety, and mobility, based on project benefits versus excess truck user costs, which include costs of delaying travelers and freight, accident costs, and vehicle-operating costs (Shufon & Adams, 2003).

Internationally, the Highway Development and Management Tool (HDM-4) has been successfully used in more than 100 countries to prioritize highway pavement investments (Cambridge Systematics et al., 2005). Requiring extensive calibration, it has seen limited application in the United States (Cambridge Systematics et al., 2005); HDM-4 was successfully calibrated for Washington State DOT use, however, to supplement the existing Washington State Pavement Management System for long-term pavement performance and investment needs (Li et al., 2005).

1.1.3 Proposed Frameworks and Tools

In addition to the a wide array of frameworks that currently serve the purposes of many DOTs, other approaches and general guidelines for handling agency assets have also been proposed.

Fundamentally, the International Infrastructure Management Manual (2006) provides guidance for developing a general asset management framework. It utilizes an optimized decision making algorithm for individual projects, and includes benefit-cost analysis and multi-criteria analysis.

Recognizing the need for better asset management guidance, National Cooperative Highway Research Program (NCHRP) Report 545 (Cambridge Systematics et al., 2005) developed analytical tools for decision-making. The tools are designed to show short-term consequences of implementing various projects within one to three years, and 10-20 year simulations resulting from various magnitudes of investments into each of the asset management classes.

The NCHRP Report 632 recognizes the importance of the Interstate Highway System (HIS) specifically, as vital to the competitiveness of the United States economy (Cambridge Systematics et al., 2009). The report develops a framework for managing interstate assets, including those other than pavements and bridges. Further, performance measures are provided, alongside details on collecting, managing and using data, as well as tools to support the program and risk management guidelines. Guidance to successfully implement the framework is also detailed.

1.2 Designated Highway Networks

The framework developed in this research could be applied over a wide range of highway systems, incorporating local and state roadways to capture the ends of freight trips, or only the major highways that are included in the Interstate and National Highway System.

The IHS includes 46,726 miles of limited access highways nationally as of 2002 (FHWA, 2009-a), and carries the highest freight volumes per mile.

The National Highway System (NHS) incorporates a 160,000-mile network of roadways, including the IHS, that are important to the nation's economy, defense and mobility (FHWA, 2010-b). The NHS contains only 4% of the nation's roads, but carries approximately 75% of heavy truck traffic (Slater, 1996). Further, it complements other freight transportation modes by offering efficient intermodal connections to 198 ports, 207 airports, 190 rail/truck terminals, and 58 pipeline terminals (Slater, 1996).

Additionally, the National Network is a companion to the NHS, a distinct

200,000-mile network of freight highways that include all of the IHS and 65,000 miles not on the NHS, while the NHS includes 50,000 miles not in the National Network (FHWA, 2010-a). The National Network supports interstate commerce through regulation on the size of trucks (FHWA, 2010-a).

To focus investment efforts for freight infrastructure, both the American Road and Transportation Builders Association (ARTBA, 2010) and AASHTO (2007) are lobbying for the establishment of Critical Commerce Corridors. These corridors would likely include most or all of the IHS, portions of the NHS, new multimodal trade corridors and new designated truck-only lanes (ARTBA, 2010).

The FAF includes a network of over 447,400 miles of highways including rural arterials, urban principal arterials, all of the IHS, NHS, and National Network, and intermodal connectors (FHWA, 2010-a).

1.3 Literature Review Discussion

Existing asset management tools used by state DOTs, i.e., Virginia Department of Transportation (VDOT), are recommended for use in the framework model to ease analysis and barriers to future implementation. If access to these resources is restricted, asset management recommendations put forth in NCHRP Report 632 are recommended as an alternative.

Numerous sources for data collected nationally have been identified, including the NBIAS, FARS, HPMS, and FAF. Incorporating nationally collected data to the framework model will facilitate use across multiple agencies.

Because the FAF provides reliable freight data and forecasts for the most important freight highways, this network is recommended for use in the development of the framework model. If necessary, additional links to commercial hubs of freight activity including major distribution centers might also be included.

TASK 2 – INVESTIGATE PERFORMANCE MEASURES

The FHWA (2010-a) defines performance measures as: “evidence to determine progress toward specific defined organizational objectives. This includes both quantitative evidence (such as the measurement of customer travel times) and qualitative evidence (such as the measurement of customer satisfaction and customer perceptions).” A multitude of performance measures are used or proposed domestically and internationally by DOTs and private firms to monitor a variety of assets and activities from truck fleet operations, costs and efficiency to infrastructure integrity and pavement quality, detailed in the following subsections (AASHTO, 2007-a; Cambridge Systematics, 2000, 2009-a; Cambridge Systematics et al., 2005, 2006-b, 2009; Czerniak et al., 1996; Forkenbrock & Weisbrod, 2001; FHWA, 2004; Hagler Bailly Services, Inc., 2000; Harrison et al., 2006; Hedlund, 2008; Li & Sinha, 2004; Lownes & Zofka, 2008; Miller et al., 2002; Neumann, 1997; Poister, 1997; Reed et al., 1993; Shaw & PBS&J, 2003; Shufon & Adams, 2003; TransTech Management, Inc., 2003; Varma, 2008).

The National Cooperative Freight Research Program (NCFRP) Report 3 aims to establish a “comprehensive, objective, and consistent set of measures of performance of the U.S. freight transportation system” (Proctor, 2010). That research found private freight sector and state DOTs to measure highly variable sets of performance measures, due in part to differing priorities in costs and network performance, respectively (Proctor, 2010).

Many state DOTs already record performance measures on their highways that include or affect freight transportation movements, such as pavement, structural, mobility, and safety measures. However, the minority of states that actually utilize freight performance measures use only a handful of disparate metrics, most of which are not even used to calibrate performance of specific state programs (Gordon Proctor & Associates, 2011).

A Minnesota study highlighted a number of freight performance measures, most of which required further development for use, including travel times for intercity routes, to intermodal terminals and to global markets, shipping rate competitiveness, crash rates by mode, and bottleneck information (Larson & Berndt, 1999); data was more readily available for measures of mobility, transportation investment, and economic cost-benefits for most freight projects. A report prepared for FHWA (Hagler Bailly Services, Inc., 2000) reviews potential performance measures and recommends seven indicators for measuring freight performance. However, not all of these indicators, such as customer satisfaction, can be readily accessed from available data sources.

A report by Shufon and Adams (2003) demonstrated a method prototyped by the New York State DOT in which performance across all categories is converted to excess user costs; for example, pavement degradation leads to increased user costs from tire and parts consumption, while accidents, detours, and congestion create added user costs from wasted time and fuel.

A number of traditional performance measures are already widely collected and used in many existing asset management systems, which directly apply to the infrastructure needs of freight transportation. These performance measures quantify the structural integrity of bridges, pavement quality, safety, and mobility, and are described in the sections below and presented in Table 1.

2.1 Structural Integrity of Bridges

A variety of measures are collected to assess the performance of bridges; many of these measures are maintained as part of the NBI. Geometric characteristics such as bridge deck width, vertical and horizontal clearances, and lane and shoulder widths are recorded and can indicate restrictions imposed upon freight traffic. Some agencies monitor network performance by tracking the average health index of bridges, the percentage of bridges with a sufficiency rating less than 50 or the percentage of bridges with deck, superstructure, or substructure NBI rating of four or less. Load ratings are also measured and are critical to freight transport. Finally, excess user costs for each bridge can be measured based on the probability of incidents and closures due to traffic volumes and lane geometry, the resulting detour length and added costs of fuel and time delay.

Recommended traditional performance measures for a freight prioritization framework are based on the NBIAS outputs, which use NBI data. Specific rules will be applied to NBIAS analysis to specify more stringent NBI Appraisal Ratings, Items 67-70, which measure the adequacy of the structure by the type of highway it is serving by structural evaluation based on loads and traffic volumes, deck geometry, vertical and horizontal clearances, and bridge restrictions (FHWA, 1995). These measures directly apply to freight flows based on limitations they may impose, or soon impose, on trucks.

2.2 Pavement Quality

Many measures are collected nationwide for the HPMS. International Roughness Index (IRI) is a standard measure of ride quality, while present serviceability rating (PSR) attempts to assess the structural integrity of the pavement. Using IRI, excess user costs can be calculated based upon tire wear and parts consumption given rougher surfaces. Pavement geometrics of lane and shoulder width are also documented, as well as skid resistance and structural adequacy. A number of indices exist that utilize IRI and pavement distress data such as the Pavement Quality Index, Rideability Index, Distress Index, and a vehicle-miles traveled (VMT) weighted pavement condition. States also monitor network performance using a number of metrics such as the percentage of miles in good, fair or poor condition, the percentage of miles below a threshold acceptable condition level, the average condition, percentage of miles with weight restrictions due to structural limitations, and the percentage of truck VMT or tonnage affected by weight restrictions.

For the purposes of a freight prioritization framework, traditional performance measures recommended to incorporate the structural adequacy of pavement should be the IRI and PSR. Selection of these measures is based on their nationwide availability and general acceptance for measuring pavement quality and structural integrity, particularly due to the importance to freight transportation.

2.3 Safety

Typical performance measures for highway safety are based on the crash rate or fatality rate. Data on vehicles involved in an incident are recorded such that the truck crash rate and truck fatality rate are also available, as well as causes attributable to construction zone, speed, and/or traffic violation crashes. Many factors can have negative safety affects, including geometrics like grade, alignment, horizontal and vertical clearances and shoulder, lane, and bridge deck widths, skid resistance, travel speed, railroad crossing adequacy, luminance, and sight distance. Safety performance can also be measured in terms of the costs associated with crashes, injuries and fatalities, or delay, and the costs to implement safety countermeasures. Further, network performance can be measured by the percentages of reduction in motor carrier crash rates, traffic exceeding the speed limit, VMT in various ranges of volume/capacity, commercial vehicles weighed, overweight commercial vehicles, commercial vehicles undergoing safety inspections, and commercial vehicles passing those safety inspections. Seat belt usage by drivers and passengers is also relevant, measured either by the number of law enforcement citations, unrestrained driver and passenger fatalities, or surveys. Finally, the Hazard Index, measured by crash/VMT by severity, and Accident Risk Index, or Safety Index also serve as metrics to a highway segment's relative safety.

For a freight-based framework, the most relevant safety performance metrics are truck crash rate, truck fatality crash rate, and geometric deficiencies that contribute to crashes.

2.4 Mobility

Mobility is often measured by travel time, delay, and speed. Related measures include standard deviation of travel time, volume/capacity ratio or level of service, density, customer ratings of trip time, reliability, congestion severity and travel cost, relative delay rate versus other routes, excess user costs due to person or freight shipment delay, intersection delay, detour length, delay due to incidents and/or congestion, percentage of highways or lane-miles congested during peak period, travel rate in minutes per mile, and variation in average speed. VMT is another common measure of mobility, including the amount or percent VMT in congestion, VMT/lane-mile per capita, and truck VMT by light duty, heavy duty, and through trips. Indices of mobility include the congestion severity index (hours of delay/million VMT), roadway congestion index (cars/road space), buffer time index (percentage of extra time needed to be on-time 95% of the time), mobility index (ton-miles * average speed), speed reduction index (ratio of speed declines across facilities), travel rate index (ratio of peak travel-time to off-peak travel time, the additional time to congestion), and misery index (a measure of the severity of congestion on the worst 20% of trips). Additional freight-related measures of mobility include the percentage of on-time shipments, the shipper's ability to reliably reach desired suppliers or markets within specified service parameters like time, cost, etc., average circuity for truck trips between selected origins and destinations, ton-miles travelled by congestion level, line-haul speed, capacity restrictions, and miles of freight routes with adequate capacity.

For the purposes of a freight transportation infrastructure needs prioritization, recommended traditional freight-relevant mobility measures include: volume/capacity ratio and truck VMT, again because of the potential for more widespread collection and use of these measures, as presented in Table 1.

Table 1: Traditional Performance Measures recommended for Prioritizing Infrastructure Improvement for Freight Transportation Needs

Focus	*Performance Measure*	*Unit/Rating*
Structural Integrity of Bridges	Structural Evaluation Deck Geometry Underclearances, Vertical & Horizontal Bridge Load Limits Posting	0-9 0-9 0-9 0-5
Pavement Quality	International Roughness Index Present Serviceability Rating	inches/mile 0-5
Safety	Truck Crash Rate Truck Fatality Crash Rate Adverse Safety Geometric Deficiencies	truck crashes/mil-VMT truck crash fatalities/mil-VMT 0-9
Mobility	Volume/Capacity Ratio Truck VMT	unitless mil-VMT
	Average Travel Speed	miles/hour

TASK 3 – MEASURING HIGHWAY ECONOMIC IMPORTANCE

3.1 Economic Impact of Freight

According to the United States DOT Bureau of Transportation Statistics, transportation services provide more than 5% to the production of the United States gross domestic product (GDP), with more than half of that attributable to for-hire or in-house trucking (FHWA, 2010-a). The FAF estimates for 2002 indicate that trucks carried almost 60% of freight tonnage, of a total 53 million tons daily, and over two-thirds of the value of goods that totaled $36 billion per day (FHWA, 2010-a).

There are several types of economic benefits that stem from highway infrastructure projects as described by the FHWA (1996). First, industry productivity can increase as a result of cost savings caused by infrastructure improvements, which in turn may stimulate the economy (FHWA, 1996; Nadiri and Mamuneas, 1996). Highway construction projects provide employment to workers, and thus benefit the local economy. Finally, by improving mobility and safety, direct benefits are provided to drivers.

Determining the comprehensive dollar value of economic benefits is difficult. Potts (2008) notes how little information exists regarding the dependence of each state's economic prosperity on transportation services provided by highways in other states. Thus, it is complicated to estimate the economic value of individual transportation projects given the established corridor's value, as a whole.

The United States Census Bureau's Commodity Flow Survey (2007), used in the FAF, maintains information on the tonnage, ton-miles, and dollar value of goods shipped within and between states and metropolitan areas by truck. Studies by Nadiri and Mamuneas (1996, 1998) and NCHRP Project 20-24(23) (2007) have quantified the macroscopic influence between major industries, transportation, and national productivity growth.

It has been argued that most transportation investments have no significant impact on economic activity (Meyer, 2001; VTPI, 2009). Indeed, while transportation investment can increase accessibility or mobility in an area, taxes, labor laws, social amenities, or other regional conditions also affect economic growth (ECMT, 2002; Peters et al., 2008; Rodrigue et al., 2009). Yet, having an efficient and modern transportation network will favor many economic changes that are, for the most part, positive (Rodrigue et al., 2009). Even so, with an already weak causal link between transportation investment and economic growth, that link is inclined to level off after reaching a certain investment threshold, e.g., the mature United States highway systems (ECMT, 2002).

However, failure to maintain investment in transportation can cause a decline in private investment in an area, resulting in declining economic conditions (Eno Transportation Foundation, 1996; Peters et al., 2008; Rodrigue et al., 2009). But in general, transportation investments have the potential to provide broad benefits to regional economies over time if made at the right time for the right locations to nurture future growth, though no guarantee of economic development can ever be predicted (ECMT, 2002; Eno Transportation Foundation, 1996; Rodrigue et al., 2009).

Calculating the economic impact of an infrastructure investment is full of uncertainty and while numerous models have been developed for this purpose, all have faults, e.g., problems with double counting benefits (ECMT, 2002). Therefore, a transportation project must be merited on the basis of transportation benefits and not just economic projections, lest inferior transportation projects be built (ECMT, 2002). Besides, even primary transportation benefits like increased safety, emissions reductions and reduced travel time can promote economic growth (ECMT, 2002).

Measuring the precise indirect economic impacts of a project may be difficult, but even a qualified one-to-five ranking can be useful, since some projects are more inclined to promote economic development than others, as demonstrated by the Oregon DOT (McMullen, 2010).

A study by Rico, Mendoza, and Mayoral (1996) recognizes the merit of identifying the economic importance of highway and rail corridors due to their contribution to national prosperity. Data was gathered at weigh stations and through the use of surveys, and then extrapolated. Four differing categories of prioritization were generated for a corridor based on truck volume, tonnage, cargo value, and a benefit-cost ratio; emphasis is placed on the notion that highways carrying a higher economic value of freight are more important than others transporting higher tonnages of low-value freight.

Another strategy examines individually the freight flows of a region's most significant commodities, then layers them together to identify the most important corridors allowing for a less data-intensive, better understood model (Souleyrette et al., 1998). Corridor importance is noted as those carrying the most tonnage of the selected commodities, however the methodology for commodity selection is not detailed.

3.2 Performance Measures of Economic Impacts of Transportation

Studies have shown that transportation investments impact economic activity directly and indirectly, but measuring that impact can be hard to assess due to the many factors that can influence the economy (Meyer, 2001; Peters et al., 2008). A review of performance measures for the impact of transportation investment on local and regional economies found a variety of measures developed to measure economic impact, but little consistency between agencies (AASHTO, 2007-a; Cambridge Systematics, 2000; Cambridge Systematics et al., 2005, 2006-b; Miller et al., 2002; Neumann, 1997; Peters et al., 2008; VTPI, 2009). These measures include freight mobility, relative unemployment, direct or indirect number of jobs created by transportation projects, job retention, whether a transportation project supports of in-state jobs, number of jobs, high-paying jobs, or licensed businesses within 'x' minutes of 'y,' economic indicators of goods movements, percent of manufactures or shippers who relocated for transportation purposes, regional truck VMT per unit of regional economic activity, shipping costs, value of goods shipped on a route, and tonnage originating or terminating in a region. Further, economic models include the use of GIS to list and classify businesses and a REMI model to show changes in business output, personal income, employment, and population as the result of infrastructure investments. Despite this diverse array of measures, there are no universally accepted metrics to accurately describe the magnitude and range of economic impacts of transportation investments (Meyer, 2001; Peters et al., 2008).

While mobility and accessibility measures are a common indicator of economic impacts, it has been found that the reduction of delays, vehicle operating costs, and accident costs have a positive impact only in areas that are already economically strong (Meyer, 2001). Regarding mobility, maximum economic benefits are derived from increased system efficiency (VTPI, 2009)

Further, job creation is often measured as an economic impact of transportation investment. This is a contentious measure, however; job creation in one area has been suggested to come at the expense of jobs or job growth elsewhere in the region (Meyer, 2001), but others argue that economic benefits are not so balanced (Eno Transportation Foundation, 1999). Moreover, direct jobs are likely to be generated as the result of any infrastructure investment, while many factors influence unemployment figures besides transportation investments (Peters et al., 2008).

Shipping costs are included as a performance measure based on analysis revealing that projects that reduce industrial transportation costs, e.g., shipping costs, will also increase productivity (VTPI, 2009). At the same time, it is argued that highway investments are not the most fruitful way to increase productivity (VTPI, 2009).

3.3 Input-Output Modeling

Input-output data is another readily available source of economic data. The Bureau of Economic Analysis (BEA) maintains regional input-output multipliers called the Regional Input-Output Modeling System (RIMS II) for areas encompassing at least one county (BEA, 2010). Multiregional input-output models have been used for transportation and freight issues (Cascetta, 2001; Hoel et al., 1967; Mahady and Lahr, 2008; Voigtlaender, 2002).

The input-output model was developed by Leontief in the middle of the 20th century (Hoel et al., 1967). In its basic form, economic data from various industries within a region are displayed in a table to show the relationships between those industries (Hoel et al., 1967; Isard, 1960). Industrial sectors are listed both in row and column headings; the production and distribution characteristics of these sectors are presented with the input to a sector from other industries displayed along a column, while that sector's output to other industries is recorded along the row (Hoel et al., 1967; Isard, 1960). Total inputs will balance total outputs when households and capital losses or profits are also included into the table (Hoel et al., 1967; Isard, 1960). The table can be expanded to include other regions and show interregional as well as intraregional economic flows (Hoel et al., 1967; Isard, 1960).

Multipliers are created by calculating percentages of the totals for the column/row; these multipliers can then be used to create projections based on speculative inputs for select industries using an iterative process where row sums are used as inputs to unknown columns, then balanced again until inputs equal outputs.

The inoperability input-output model is derived from the Leontif input-output model and shows the economic interdependencies of different industrial sectors. Thus, it can show the economic impact to all sectors due to a disruption to one or more sectors. The inoperability input-output model was first presented by Haimes and Jiang (2001) and further refined and related to highway applications (Crowther, et al., 2004; Haggerty, et al. 2008; Haimes et al., 2005-a; Haimes et al., 2005-b).

Haimes and Jiang (2001) develop an application of the inoperability input-output model to infrastructure instead of commodities, for instance between power plants, the transportation sector, and hospitals. However, the methodology might be able to show, for example, the dependence of “Bridge A” upon “Bridge B” in the network. The authors emphasize, however, extensive data collection and data mining would be necessary to assemble the Leontif matrix, showing the relations and reliance between various pieces of infrastructure. While this application focuses on the interdependence of the infrastructure, it is my opinion that it would not adequately demonstrate the dependence of industrial sectors on the trucking sector, and thus highway infrastructure.

In the context of terrorism, the inoperability input-output model has been applied to Hampton Roads tunnels in Virginia (Haimes et al., 2004). This study examined the impact of a closure or reduced capacity in the tunnel. Although the inoperability input-output model is a demand-based model, it can be applied in this case because a reduction in supply necessitates reduced demand; in other words, consumption will adjust from “normal” levels in the event that supply is reduced (Haimes et al., 2004).

Mahady and Lahr (2008) note in their use of the input-output model that transportation cost reductions are likely going to lower producer costs, however these benefits can also be interpreted as production increases. Thus, in their study they justify the conversion of travel time reductions to cost savings. This cost savings reduces industries’ input to the trucking sector and translates to increased productivity in other sectors of the economy.

3.4 Measuring Highway Economic Importance Discussion

For this study, input-output multipliers are obtained from the BEA. An inoperability input-output model is developed to identify those industrial sectors most dependent upon the trucking sector. Then using national commodity flow information available from the FAF regions, specific route assignments can be made to the selected freight highway network. Links used to transport more commodities of the more truck transportation-dependent industrial sectors are designated a higher rank of economic importance.

Excess trucking costs can be calculated for a highway link based on a number of factors. This study will utilize AADTT from FAF to estimate excess trucking costs for mobility based on potential travel time saving, and for safety based on a potential reduction in truck crashes. Additional measures of excess trucking costs might be derived using AADTT and detour length, and estimated congestion based on capacity of alternate route given a closure due to infrastructure failure (structural).

Finally, the economic hindrance from inefficiency of excess trucking costs estimates a value of increased economic productivity that is otherwise spent on transportation costs, and can be calculated separately for each highway link. Based on the commodities on each highway link, the trucking sector input can be recalibrated in the input-output model based on the sectors that use the link to determine the economic impacts to other sectors given excess trucking costs for each highway link in the network for a given period (Mahady and Lahr, 2008).

The development of these three economic metrics is detailed in a demonstration methodology in Appendix A. In short, these three economic metrics are:

1. *Relative economic importance* of highway links based on sectors most dependent upon the trucking sector, according to a disruption to the trucking sector using the inoperability input-output model, and an origin-destination model with route assignments for specific commodities of those truck-dependent sectors.

2. *Excess trucking costs* of highway links based on the given AADTT and estimated reduction in delay based on A) potential travel time improvements (mobility) and B) potential reduction in truck crashes given an infrastructure improvement. Additional measures that might be considered include excess trucking costs based on the degree of congestion and delays expected from a closure due to infrastructure failure (structural) given AADTT and detour length of an alternate route. Trucking costs for mobility purposes are based on TTI's Urban Mobility Report value of commercial vehicle time at $105.67/hour (Schrank et al., 2010).

3. *Economic hindrance from inefficiency of excess trucking costs* estimates a value of increased economic productivity that is otherwise spent on transportation costs, and can be calculated separately for each highway link. In short, excess trucking costs require industries to pay costs on shipping that might otherwise be invested elsewhere and spurn economic development, such as expanding business, increasing employment, etc. Based on the commodities on the highway links (from metric 1), the trucking sector input can be recalibrated in the input-output model based on the sectors that use the link to determine the economic impacts to other sectors given excess trucking costs (from metric 2) for each highway link in the network for a given period (Mahady and Lahr, 2008).

Double counting among these metrics could occur it taken together, particularly metrics 1 and 3. Thus, it is recommended that these two measures be applied separately.

TASK 4 – LINK ECONOMIC IMPORTANCE AND FREIGHT HIGHWAY INFRASTRUCTURE NEEDS

Following the development of the economic performance measures in the previous section, the next step is to incorporate these measures into an asset management system. This will provide a method to prioritize freight highway infrastructure needs for selected corridors.

4.1 State of Practice

States already use asset management tools to prioritize infrastructure needs as identified in Task 1. This research builds upon existing tools for smoother integration with current practice, rather than building an entirely new comprehensive asset management tool. The decision model for this research is detailed below as a module within an existing state DOT asset management tool.

Currently, VDOT uses the Asset Management System to identify infrastructure needs for existing pavement and bridge assets. For safety needs, the Virginia Highway Safety Program, a part of the Highway Safety Improvement Program conducts road safety assessments (RSA, also known as road safety audits) and uses crash rates to prioritize locations with safety needs. Many freight relevant performance measures are already captured by these systems, including those related to structural soundness, pavement quality, and mobility, which are housed in the VDOT Archived Data Management System (ADMS).

Additional freight measures identified in Tasks 2 and 3 might be integrated as a separate freight module. The distinction of truck-related crashes and fatalities from total crashes and fatalities, for instance, may lead to the identification of hotspots in need of specialized safety treatments for trucks. Alternatively, these freight metrics might be incorporated into the decision-making process for specific functional classifications in the network, such as interstates and principal arterials. The resulting output will be a list of infrastructure needs for specified freight corridors listing current excess trucking costs, projected regional economic benefits, and the prioritized ranking. A proposed schematic for incorporating additional freight-relevant measures from the FAF, as well as those proposed in this research, are shown below in Figure 3, where dashed lines represent proposed links for inclusion of freight considerations to the existing asset management system.

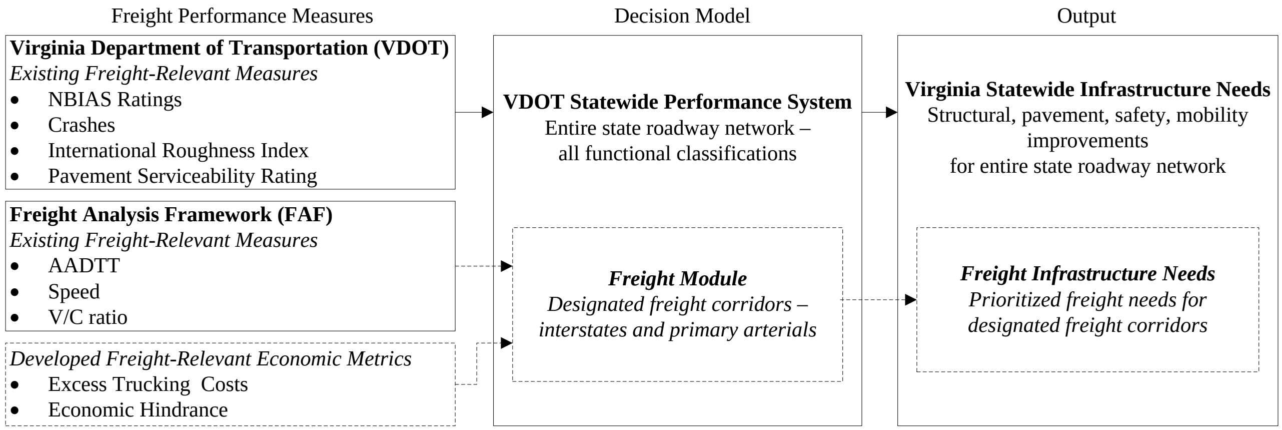


Figure 3. Example of integrating new metrics into an existing asset management system

4.2 Developing a Decision Model to Prioritize Freight Highway Infrastructure Needs

As mentioned for the Virginia Statewide Planning System, it is likely that a given asset management tool will already incorporate some freight-relevant performance measures. To avoid duplication, the inclusion of these performance measures in the freight highway infrastructure decision model is discouraged. Instead, the focus should be placed upon freight-relevant performance measures that are readily available for relevant freight corridors, such as those detailed in Task 2.

It cannot be expected that all freight-relevant performance measures will be consistently available for all regions, or even for specific corridors or areas within a region. Thus, where data is unavailable for all corridors or areas to be evaluated in the decision model, either default or qualified values may be employed as a placeholder or best guess for comparison.

The Virginia Statewide Planning System, as depicted in Figure 3 already collects a number of freight-relevant performance measures. These measures include National Bridge Investment Analysis System (NBIAS) ratings for structures, the International Roughness Index (IRI) and Pavement Serviceability Rating (PSR) for pavement quality, and crashes for safety, among others.

For the purposes of this research, the freight module that will be developed and demonstrated that includes additional freight measures gathered from the FAF, VDOT crash database, and freight-relevant economic metrics developed herein. As mentioned in Task 3 above, to eliminate double counting only select measures developed in this research, namely excess user costs for trucks and economic hindrance will be used.

Necessarily, the output from the freight module of the decision model will be a prioritized list of freight highway infrastructure needs. This research will examine several possibilities for the decision model, including an equal weighting approach, where prioritization will be determined based on the sum of equally scaled performance measures for each identified need, and weighted approach for both mobility and safety measures, in which more emphasis is placed on a specific goal, e.g., improving mobility. This approach is detailed further in Sinha and Labi (2007). For example, given a list of freight infrastructure needs, for each performance measure, the “best” measured value would be assigned a value of 1, and the “worst” measured value would be assigned the value of 5, and each measure in between would be scaled accordingly.

For instances where not all identified needs contained values for all performance measures, a value might be estimated using professional judgment. Less preferably, a default neutral value of 3 might be assigned for missing values.

Note that when an agency wishes to emphasize certain values more than others, e.g., mobility measures, to accomplish specified mobility or safety-related objectives, for example, the scale of those values might be adjusted accordingly by multiplying by a constant or using a larger scale,.

A sample of how the freight module could function is given in Table 2, and will be demonstrated further in the proofs of concept in Task 5. This table gives an example where three performance measures (i.e., PM 1, PM 2, PM 3) are given for three identified needs (i.e., A, B, C, with the exception of PM 3 for need C). The performance measures are rated accordingly on a scale of 1 to 5 with the “best” measures receiving a 1.00 rating, and the “worst” measures receiving a 5.00 rating, unknown measures being assigned a 3.00, and remaining measures being interpolated.

Table 2. Demonstration of freight module with sample values of expected improvement

Corridor with Identified Need for Improvement	Performance Measures			Scaled Rating (1-5)			Sum	Rank
	PM 1: Structural Integrity	PM 2: Pavement Quality	PM 3: Truck Crashes	PM 1	PM 2	PM 3		
Route 1	0.6	190	5	1.00	5.00	5.00	11.00	1
Route 2	0.9	103	3	2.50	1.72	1.00	5.22	3
Route 3	1.4	84	4	5.00	1.00	3.00	9.00	2

TASK 5 – CONDUCT PROOFS OF CONCEPT

In this section, the methodology, as described in previous sections, shown in Figure 1 and Figure 2 above, and detailed in Appendix A, is demonstrated for two case study corridors in Virginia: U.S. 460 and U.S. 29. Both case studies weigh the prospects of building new highway infrastructure and capacity against prioritizing spot improvements on the existing roadways.

Specifically, the first case study investigates the potential economic impact of a new tolled expressway roughly paralleling U.S. 460 from Suffolk to Petersburg in eastern Virginia. The second case study examines the economic impact to areas within the U.S. 29 corridor of a new bypass around a heavily developed area on the north side of Charlottesville.

5.1 Developing the Inoperability Input-Output Model

The steps described in this section are based on the methodology presented in Figure 4 below, and more specifically described in Appendix A. “Make” and “use” tables (which respectively show monetary values of column commodities produced by various row industries, and monetary values of row commodities consumed by various column industries) were obtained from the BEA. These tables, as well as all the calculated tables described below derived, are shown in Appendix B.

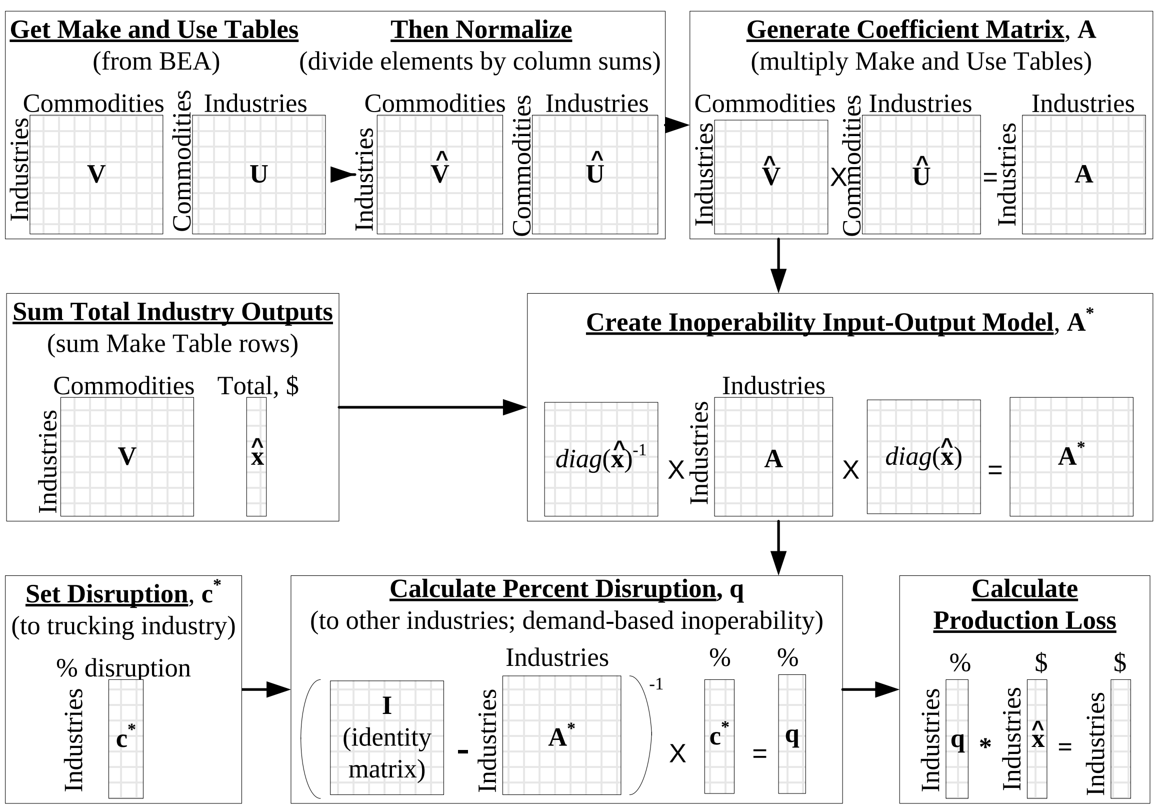


Figure 4. Steps for development of inoperability input-output model and calculation of impacts of an industry disruption (e.g., trucking) to other industrial sectors

Following the procedure more specifically described in Appendix A, the "make" and "use" tables were normalized and multiplied to create an industry-by-industry technical coefficient matrix, **A**, which gives the proportion of industry *i* inputs to *j* relative to the total production output of industry *j*.

Next, the total industry outputs, that is, the "normal" total production vector $\hat{\mathbf{x}}$ was calculated by multiplying the "make" table with a unity vector (whose elements are all ones and is also known as a summation vector).

Using these input-output tables, a demand-based model, the inoperability input-output model, was derived. A unit value of $1 to the trucking sector is used in the inoperability input-output to represent changes in trucking costs caused by a disruption (or an improvement). The inoperability input-output model then shows sector disruptions that are proportional to the value of the original disruption, which is possible since the input-output model is linear; thus, the relative economic impact to a sector is based on an impact to the trucking sector (for example, a $1 disruption to the trucking sector will disrupt $.05 of sector A, $.25 of sector B, etc.). Note that the unit disruption is not intended to represent any specific incident or congestion for any specific point; instead, it is used to show the various industrial sectors' dependence on the trucking sector for the study area. Thus, for any given incidents or congestion on specific highways in Virginia, it can be known which sectors will be most impacted by a disruption. Also, since the input-output model is linear, these relative values can be multiplied by a specific value representing a trucking disruption event to show indirect impacts for an event.

For these proofs of concept, ten FAF commodities were selected for analysis, based on their top rankings as Virginia critical commodities handled by truck in the state according to the Virginia Statewide Multimodal Freight Study, as shown in Table 3 (Cambridge Systematics, 2010).

Table 3: Virginia's Top Critical Commodities Handled by Truck

Leading Virginia Truck Tonnage Commodities (2004)	*Truck-hauled Tonnage*	*Truck Mode Share, % Tonnage*	*Proof of Concept Inclusion*
Nonmetallic Minerals	99,947,446	89%	✓
Secondary Traffic (warehouse dist.)	62,524,254	100%	
Clay, Concrete, Glass, or Stone	36,171,451	92%	✓
Lumber or Wood Products	32,867,249	95%	✓
Food or Kindred Products	31,112,374	93%	✓
Petroleum or Coal Products	27,883,789	80%	
Chemicals or Allied Products	24,248,272	86%	
Pulp, Paper, or Allied Products	9,957,320	80%	
Transportation Equipment	9,922,172	87%	
Farm Products	9,728,832	81%	

Source: Virginia Statewide Multimodal Freight Study (Cambridge Systematics, 2010)

These selected commodities are represented by disparate FAF Commodities and BEA Industries used in the input-output model, as shown in Table 4. Also shown are values from the inoperability input-output model relating to the percent disruption and relative dollar loss for a unit disruption to the trucking sector for BEA industries, and the relative dollar loss values for FAF commodities used in the proofs of concept. The connections shown in Table 4 between BEA industries and FAF commodities is based on the relations used for the development of the FAF model (Southworth, et al., 2011).

Because it is representative of the entire state of Virginia, this developed inoperability input-output model is applicable for both case study examples presented below.

Table 4: Selected FAF Commodities and BEA Industries for the Proofs of Concept, and relative economic impact values from the inoperability input-output model

FAF Commodity	**BEA Industry (inoper. input-output model)**	**Percent disruption (q)**	**$ loss, ratio**	**Derived Commodity $ loss ratio**
Cereal grains	Farms	7.77E-11	0.00153	0.00193
	Food and beverage and tobacco products	1.15E-10	0.00233	
Meat/seafood	Farms	7.77E-11	0.00153	0.00193
	Food and beverage and tobacco products	1.15E-10	0.00233	
Milled grain prods.	Farms	7.77E-11	0.00153	0.00193
	Food and beverage and tobacco products	1.15E-10	0.00233	
Other foodstuffs	Farms	7.77E-11	0.00153	0.00193
	Food and beverage and tobacco products	1.15E-10	0.00233	
Building stone	Mining, except oil and gas	1.25E-10	0.00245	0.00250
	Support activities for mining	1.31E-10	0.00257	
Natural sands	Mining, except oil and gas	1.25E-10	0.00245	0.00250
	Support activities for mining	1.31E-10	0.00257	
Gravel	Mining, except oil and gas	1.25E-10	0.00245	0.00250
	Support activities for mining	1.31E-10	0.00257	
Nonmetallic minerals	Mining, except oil and gas	1.25E-10	0.00245	0.00250
	Support activities for mining	1.31E-10	0.00257	
Logs	Forestry, fishing, and related activities	6.06E-11	0.00118	0.00165
	Wood products	1.09E-10	0.00213	
Wood products	Furniture and related products	2.49E-11	0.00049	0.00130
	Wood products	1.09E-10	0.00213	

5.2 Gathering Safety Data

Baseline safety data was gathered to use for both proofs of concept examples. All of this data is publically available through VDOT (2012-a). Both proofs of concept examples are included in the Virginia Primary Roadway system and so this statewide data was used for a baseline for current conditions. IHS crash data was selected to assist with estimating crashes on the proposed improved roadways in the proofs of concept, since each of these are to be limited access facilities built to similar standards. Because crash data includes several years of latency, the latest available data is only through 2007.

In order to normalize crash data, 2005-2007 daily vehicle-miles traveled (VMT) data was gathered for each Federal vehicle class, as shown in Table 5 for both primary and interstate roadways. Daily VMT was summed for vehicle classes 5-14, which represent daily truck VMT (ODOT, 2012), as shown below, to discern the total daily truck VMT for each year. This value was multiplied by 365 to have a value of total annual truck VMT per year for both primary and interstate roadways.

Table 5: Daily Truck Vehicle-Miles Traveled by Federal Vehicle Class on Virginia Primary and Interstate Roadways

Federal Vehicle Class	Federal Vehicle Class Description	Primary Roadways			Interstate System		
		2005	2006	2007	2005	2006	2007
5	2-axle, 6-tire, single unit trucks	819005	817560	840478	514412	465642	444266
6	3-axle, single-unit trucks	620369	625110	625405	394680	355206	347305
7	4 or more axle, single-unit trucks	157314	162354	161749	71596	69916	74096
8	4 or fewer axle, single-trailer trucks	352059	341296	316065	295770	364727	429139
9	5-axle, single-trailer trucks	2467536	2655747	2605762	6748732	6850638	6932382
10	6 or more axle, single trailer trucks	68557	83784	85092	83064	80175	84523
11	5 or fewer axle, multi-trailer trucks	66048	71646	72254	293672	299597	302182
12	6-axle, multi-trailer trucks	14890	15620	14280	106773	104581	98867
13	7 or more axle multi-trailer trucks	574	201	167	591	525	616
Total Daily Truck VMT		4566352	4773318	4721252	8509290	8591007	8713376
Total Annual Truck VMT (x100 million)		16.7	17.4	17.2	31.1	31.4	31.8

Source: VDOT, 2012-b.

Next, truck crash statistics for 2005-2007 were gathered for both primary and interstate roadways for the entire state of Virginia, and are organized by crash type in Table 6. In order to more easily compare the number of crashes across multiple years while still accounting for severity, a method from Garber and Hoel (2009) was applied that weights fatal, injury, and property damage crashes on a scale of 12:3:1. These values are shown in the bottom row of Table 6. All values in this table are then averaged across 2005-2007 separately for primary and interstate roadways.

Table 6: 2005-2007 Truck Crashes on Virginia Primary and Interstate Roadways

Truck Crash Type	All Truck Crashes on Virginia Primary Roadways				All Truck Crashes on the Interstate System in Virginia			
	2005	2006	2007	2005-2007 Average	2005	2006	2007	2005-2007 Average
Fatal Crash	55	48	48	52	28	32	31	30
Persons Killed	64	51	57	58	29	38	36	34
Injury Crash	1001	848	795	925	952	919	779	936
Persons Injured	1448	1220	1122	1334	1446	1325	1141	1386
PDO Crash	1757	1577	1412	1667	1973	1790	1685	1882
Total Crash	2813	2473	2255	2643	2953	2741	2495	2847
Crash Severity Number (12:3:1)	5420	4697	4373	5059	5165	4931	4394	5048

Source: VDOT, 2012-a.

Truck crash values shown in Table 6 were normalized using the total annual truck VMT values for each year from Table 5. The resultant truck crash rates were divided by 100 million in order to give Truck crash rates per 100 million truck VMT, as depicted in Table 7.

Table 7: 2005-2007 Truck Crash Rates on Virginia Primary and Interstate Roadways

Truck Crash rates per 100 million Truck VMT	Truck Crash Rates on Virginia Primary Roadways				Truck Crash Rates on the Interstate System in Virginia			
	2005	2006	2007	2005-2007 Average	2005	2006	2007	2005-2007 Average
Fatal Crash Rate	3.3	2.8	2.8	2.9	0.9	1.0	1.0	1.0
Persons Killed Rate	3.8	2.9	3.3	3.4	0.9	1.2	1.1	1.1
Injury Crash Rate	60.1	48.7	46.1	51.6	30.7	29.3	24.5	30.0
Persons Injured Rate	86.9	70.0	65.1	74.0	46.6	42.3	35.9	44.4
PDO Crash Rate	105.4	90.5	81.9	92.6	63.5	57.1	53.0	60.3
Total Crash Rate	168.8	141.9	130.9	147.2	95.1	87.4	78.4	91.2
Crash Severity Rate (12:3:1)	253.8	269.6	325.2	261.7	166.3	157.3	138.2	161.8

5.3 Proof of Concept #1: U.S. 460 Expressway – Hampton Roads to Petersburg, VA

The U.S. 460 corridor stretches west from Hampton Roads as a four-lane non-divided highway with numerous ground-level crossings, including 12 signalized intersections, before connecting with Interstates 295, 95, and 85 in Petersburg, then continuing west into central and western Virginia as a two-lane roadway. The seaports in Hampton Roads generate significant volumes of truck traffic into and out of that region via the primary interregional highways of the region, which include Interstate 64, U.S. 13, U.S. 17, U.S. 58, and U.S. 460. Each of the Hampton Roads Bridge-Tunnels, i.e., Interstate 64 and Interstate 664, are severe bottlenecks in the region for north-south traffic in the area. As depicted in Figure 5, while Interstate 64 enters the Hampton Roads area from the northwest as the only limited-access highway for the region, U.S. 460 enters from the west on the south side of Hampton Roads, serving as a bypass to the bridge-tunnels for traffic to destinations on the southern side of the harbor.

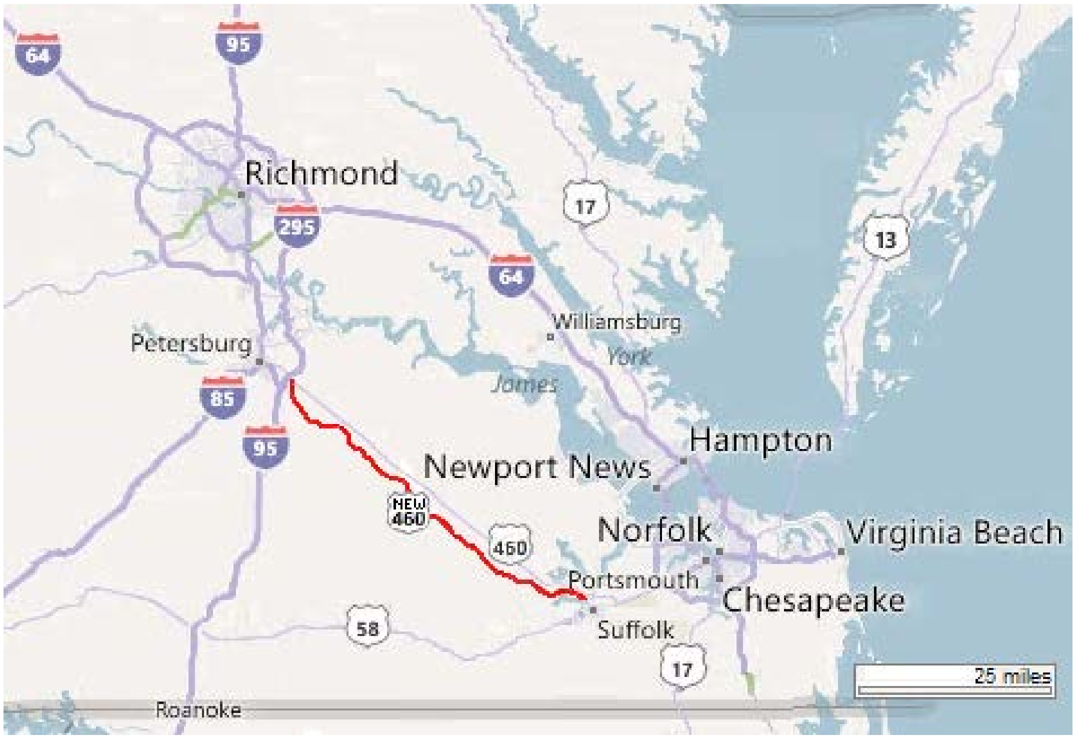


Figure 5. Map of eastern Virginia showing U.S. 460 (existing and proposed "new" in red) and other major routes in the region

As of 2012, the Virginia Department of Transportation (VDOT) continues to explore a public-private partnership (PPP) agreement to develop a four-lane divided, limited-access tolled expressway that would parallel the existing four-lane U.S. 460 between Suffolk in the east near Hampton Roads to the junction with Interstate 295 in the west near Petersburg. This project is intended to address increased freight volumes and support local economic development plans, as well as address general corridor deficiencies, improve safety, reduce travel delay, and improve hurricane evacuation capabilities (VDOT, 2012-c; FHWA & VDOT, 2005).

Specifically, travel demand forecasts show increased demand for an improved expressway versus the existing highway in 2026 forecasts, ranging from 160% to 425% over existing demand for various segments (FHWA & VDOT, 2005). While the travel time on the existing highway was 73 minutes in 2003, it is forecast to be 81 minutes and 60 minutes on the existing and proposed highways, respectively, in 2026; in other words, the proposed expressway is projected to have a 21 minute or 26% travel time savings in 2026 for the length of the route (FHWA & VDOT, 2005). Truck percentage is also expected to increase from 23%-30% in 2003 to 30%-36% in 2026 on the existing highway, or 28%-38% on an improved highway in 2026 (FHWA & VDOT, 2005). Additionally, the proposed expressway would be a safer facility type than the existing roadway, which has historically had a disproportionately high crash rate for its facility type (FHWA & VDOT, 2005).

While this 55-mile toll road would provide a better connection to the region, the proposed truck toll is $.21 per mile ($11.72 for a complete one-way trip), with a 3.5% annual toll escalation (VDOT, 2012-c).

5.3.1 Calculating U.S. 460 Economic Importance

Due to the geographic position of Hampton Roads on the east coast, this study assumed that pass-through traffic on the east-west U.S. 460 would have its origin or destination in the Hampton Roads FAF region. Data retrieved from the FHWA FAF was organized and sorted into three major geographic groups for route assignment purposes; two individual FAF regions, Richmond and Remainder of Virginia, were retained as separate groups as shown in Figure 6, due to close proximity to the Hampton Roads FAF region. The three major groupings, shown in Figure 6, are likely to have differing route splits between the choices offered by Interstate 64 and U.S. 13, U.S. 17, U.S. 58, and U.S. 460.

Route assignment to the five regions was estimated based on travel time estimations from Google Maps, and empirical knowledge of the quality of the route, i.e., two-lane vs. four-lane vs. four-lane limited access. This was validated and further refined by summing kilotons of selected commodities for each route (see Table 8), then comparing the proportional FAF AADTT, i.e., truck volume, estimations given for those routes, as shown in Table 9.

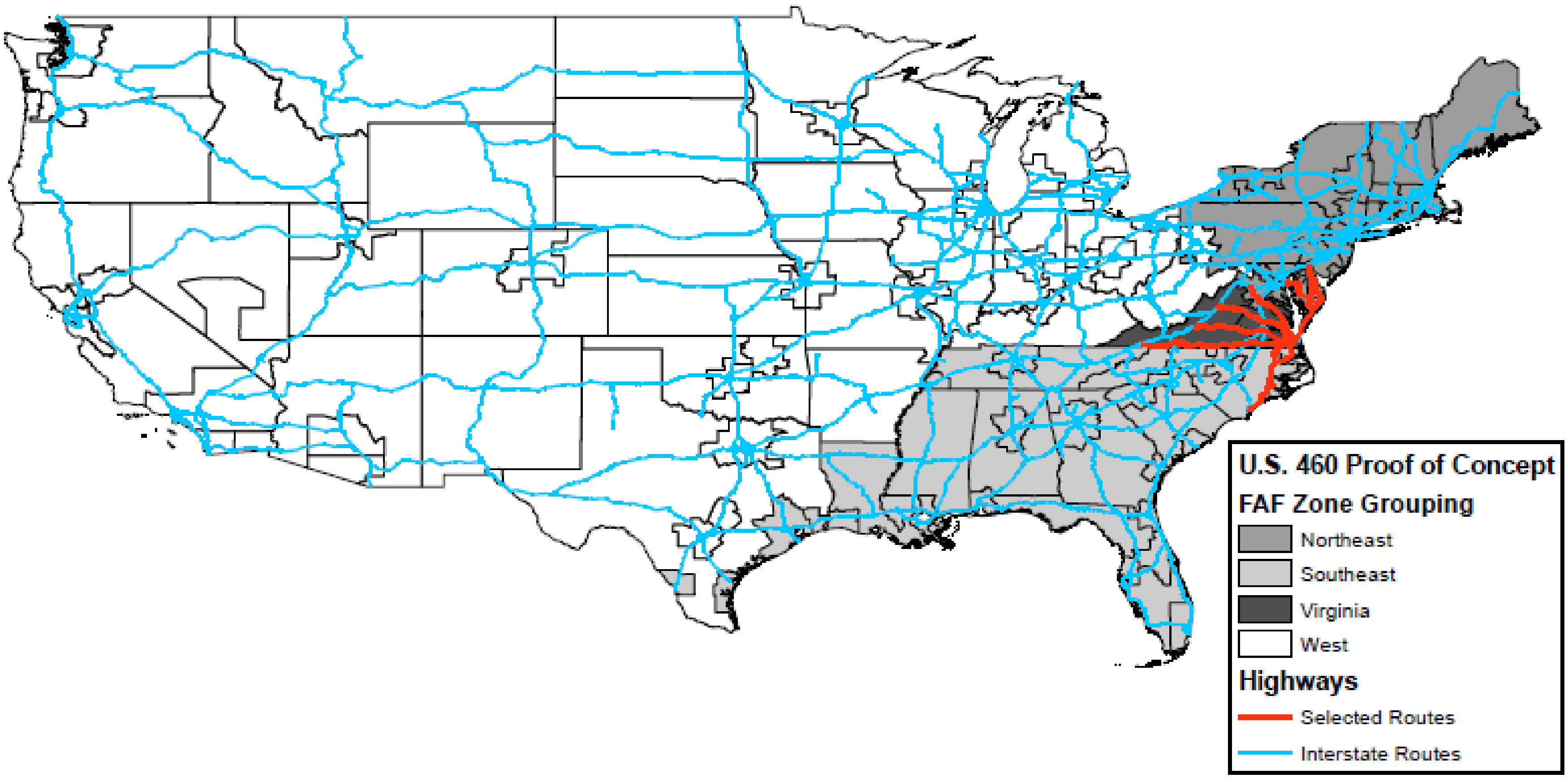


Figure 6. FAF region groupings for origin-destination route assignment designation to/from the Hampton Roads area given available, selected routes

Table 8: Kilotons of Commodities by grouped FAF region

Commodity	North	South	West	Richmond	Remainder of Virginia
Building stone	44.7	24.0	19.7	15.7	2.1
Cereal grains	127.0	216.0	213.8	354.2	147.9
Gravel	291.7	14.2	0.2	441.9	113.2
Logs	52.6	13.1	6.6	56.1	93.9
Meat/seafood	224.5	404.3	137.5	31.0	65.7
Milled Grain Products	57.8	77.9	37.2	9.9	0.5
Natural Sands	2.3	658.1	26.2	8.3	4.5
Nonmetallic minerals	281.6	599.0	25.7	74.2	10.3
Other foodstuffs	771.1	330.2	279.8	260.8	254.5
Wood Products	367.0	703.3	234.4	200.0	446.1
Total for Region	2220.4	3040.2	981.2	1452.0	1138.7

Table 9: Route assignment estimations by grouped FAF region

Route	AADTT 2007		FAF grouped region origin-destination direction from Hampton Roads (% of total KiloTons)					
	Volume	% of total	North	West	South	Richmond	Virginia remainder	Route Total
Interstate 64	3870	34.9	12.2	6.4	1.0	10.9	4.1	34.6
U.S. 13 (north)	743	6.7	5.6	0	0	0	1.1	6.7
U.S. 13 (south)	262	2.4	0	0	2.4	0	0	2.4
U.S. 17 (north)	172	1.5	0.9	0.4	0	0	0.2	1.5
U.S. 17 (south)	1224	11.0	0	0	11.0	0	0	11.0
U.S. 58	2562	23.1	0	1.1	17.6	0	4.1	22.8
U.S. 460	2271	20.5	6.1	3.2	2.1	5.4	4.1	20.9
Total	11,104	100	24.9	11.0	34.1	16.3	13.7	100

It might be expected that a new, improved expressway paralleling U.S. 460 would not only serve the truck traffic on the existing route, but also attract truck traffic from other, more congested neighboring routes I-64 and U.S. 58, particularly trucks that might have to cross one of the bridge-tunnels to reach their origin or destination. However, for the purposes of this study, despite the potential benefit that existing truck traffic on I-64 and U.S. 58 might derive from the new expressway, only existing truck volumes will be analyzed. For instance, in uncongested conditions, I-64 will still provide a faster travel time than the U.S. 460 expressway to northern region destinations; however, given congestion at the Hampton Roads Bridge-Tunnels, the U.S. 460 expressway may offer a shorter travel time. Accurately determining the specific volume or proportionate of truck traffic that not only might experience faster travel times on U.S. 460 given congestion levels at the bridge-tunnels, but also would make that choice as a result of traveler information is too difficult to ascertain.. The percentages in Table 9 above were applied to the commodity tonnage values in Table 8, to give the commodity tonnage values for this proof of concept in Table 10. The values generated from the inoperability input-output model are applied to this commodity tonnage to provide values of economic importance, which are shown in Table 10; as highlighted in bold text, the value of economic importance for U.S. 460 is 3.56.

Table 10: Total Commodity Tonnage by Route for U.S. 460 Proof of Concept

	Kilotons by route			Input-Output Economic Importance by route		
Commodity	I-64	U.S. 460	U.S. 58	I-64	U.S. 460	U.S. 58
Building stone	45.2	24.0	14.9	0.113	0.060	0.037
Cereal grains	473.4	268.9	176.8	0.914	0.519	0.341
Gravel	472.7	254.1	41.5	1.186	0.637	0.104
Logs	95.9	62.7	35.7	0.159	0.104	0.059
Meat/seafood	242.6	149.7	241.9	0.469	0.289	0.467
Milled Grain Products	59.0	33.1	43.9	0.114	0.064	0.085
Natural Sands	43.1	52.2	343.8	0.108	0.131	0.862
Nonmetallic minerals	224.1	140.9	315.0	0.562	0.353	0.790
Other foodstuffs	801.6	454.2	274.3	1.548	0.877	0.530
Wood Products	605.2	401.9	520.4	0.790	0.525	0.680
Total for Region	3062.9	1841.7	2008.3	5.963	**3.560**	3.956
Ratio with I-64 Regional Total	1	0.6013	0.656	1.000	0.597	0.663

5.3.2 Calculating U.S. 460 Excess Trucking Costs

Excess trucking costs for mobility and safety are calculated for this proof of concept based on travel time savings and potential truck crash reduction for a scenario comparing the existing U.S. 460 with the projected benefits of a completed U.S. 460 expressway.

A conservative estimate of total excess trucking costs due to travel time savings can be derived using 2007 AADTT values from the FAF and the U.S. 460 Environmental Impact Statement estimates of travel times. A value of commercial vehicle time to calculate excess costs is $105.67 as reported in TTI's Urban Mobility Report (Schrank et al., 2010). Assume that with existing conditions, the new expressway would have a travel time of 60 minutes versus 73 minutes for the existing route. Thus, trucks incur costs due to an additional 13 minutes of travel, resulting in an excess trucking cost of almost $23 per truck, or using the 2007 AADTT of 2271 trucks, a total excess trucking cost of nearly $52,000 per day, totaling over $19 million annually for only travel time savings on the new expressway alone.

Excess trucking costs can similarly be calculated from other measures, such as projected safety benefits. Crash data on a compact disc (CD) for the entire state of Virginia for 2005-2010 were obtained directly from the VDOT Central Office, by request. Crash data on this CD were organized in a series of tables. In order to glean relevant truck crash data specifically for the U.S. 460 study corridor, two tables (i.e., “crash document” and “crash vehicle”) had to be joined by the crash document number. Several filters were applied to this data. Data were limited to crashes that:

- Include vehicle classes that identify trucks;
- Occurred on U.S. 460; and
- Occurred between Latitude/Longitude points of either end of the study area (37.188083,-77.323837 and 36.767225,-76.603681), or
- Occurred between state designated mileposts of the study area (324.09 to 373.89).

Note that both latitude/longitude coordinates and mileposts were used to locate relevant crash data since neither of these fields was consistently completed for all crash data for all years. This raw crash data for the U.S. 460 study corridor is presented in Table C-1 of Appendix C. The filtered crash data relevant to the U.S. 460 study corridor for years 2005-2010 is presented in Table 11.

Table 11: 2005-2010 Truck Crashes by Crash Type on U.S. 460 Study Corridor

Truck Crash Type	Truck Crashes on U.S. 460 Study Corridor						
	2005	2006	2007	2008	2009	2010	2005-2010 Average
Fatal Crash	1	4	4	4	0	3	2.7
Persons Killed	3	4	4	4	0	3	3.0
Injury Crash	13	15	12	10	13	6	11.5
Persons Injured	16	22	20	11	15	8	15.3
PDO Crash	19	33	22	10	32	11	21.2
Total Crash	33	52	38	24	45	20	35.3
Crash Severity Number (12:3:1)	70	126	106	88	71	65	87.7

To normalize the data, the distance of the existing segment to be replaced was determined to be 50 miles based on the farthest endpoints of crash data. The 2007 AADTT of the existing segment was gathered for each segment within the study corridor from the FAF and, using the mileage of each segment, converted to a daily truck VMT of 119,020 for the total length of the study corridor (this raw data is shown in Table C-3 of Appendix C). This value was multiplied by 365 to get annual truck VMT. These values are presented in Table 12.

Table 12: Measures required for Safety Calculations for U.S. 460 Study Corridor

Measures	U.S. 460 Study Corridor
Distance	50 miles
FAF AADTT 2007	2377 (weighted average)
Daily Truck VMT	119020
Total Annual Truck VMT (x100 million)	0.434423

Truck crash rates for the U.S. 460 corridor were derived simply by dividing values presented in Table 11 by the value for total annual truck VMT presented in Table

12. The calculated truck crash rates for the years 2005-2010 by crash type for the U.S. 460 study corridor are presented in Table 13.

Table 13: 2005-2010 Truck Crash Rates by Crash Type on U.S. 460 Study Corridor

Truck Crash Rate per 100 million Truck VMT	Truck Crash Rates on U.S. 460 Study Corridor						
	2005	2006	2007	2008	2009	2010	2005-2010 Average
Fatal Crash Rate	2.3	9.2	9.2	9.2	0.0	6.9	6.1
Persons Killed Rate	6.9	9.2	9.2	9.2	0.0	6.9	6.9
Injury Crash Rate	29.9	34.5	27.6	23.0	29.9	13.8	26.5
Persons Injured Rate	36.8	50.6	46.0	25.3	34.5	18.4	35.3
PDO Crash Rate	43.7	76.0	50.6	23.0	73.7	25.3	48.7
Total Crash Rate	76.0	119.7	87.5	55.2	103.6	46.0	81.3
Crash Severity Rate (12:3:1)	161.1	290.0	244.0	202.6	163.4	149.6	201.8

Compared with truck crash rates on other Virginia Primary Roadways that were presented in Table 7, only the average truck fatality crash and persons killed rates are higher on the U.S. 460 study corridor at a ratio of 6.1 to 2.9 and 6.9 to 3.4, respectively. Similarly, when compared with crash rates on the Virginia interstate highways in Table 7, which have similar characteristics as the proposed U.S. 460 expressway, only average truck fatality crash and person killed rates on the existing roadways are higher. These comparisons are presented in Table 14 below.

The difference between the current and interstate-grade proposed expressway are presented for fatality crash and persons killed rates, alongside the potential annual reduction in the number of fatal crashes and persons killed, given the existing truck VMT in the study corridor. Using a value of $7.2 million given by the Federal Motor Carrier Safety Administration (FMCSA, 2008) as the cost of each medium/heavy vehicle fatality crash, it can be estimated by multiplying with the potential 2.2 crashes reduced that $15.8 million in annual excess trucking costs (or $43,400 per day) can be potentially eliminated with the construction of the proposed U.S. 460 expressway.

Table 14: Comparison of Average Crash Rates for U.S. 460 Study Corridor to All Virginia Primary and Interstate Roadways

Average Annual Virginia Truck Crash Rates per 100 million Truck VMT					
Truck Crash Rate Type	U.S. 460 Study Corridor 2005-2010	Interstate System 2005-2007	Primary Roadways 2005-2007	U.S. 460 to Interstate System Difference	Potential Annual Crash Reduction
Fatal Crash Rate	6.1	1.0	2.9	5.2	2.2
Persons Killed Rate	6.9	1.1	3.4	5.8	2.5
Injury Crash Rate	26.5	30.0	51.6	-	-
Persons Injured Rate	35.3	44.4	74.0	-	-
PDO Crash Rate	48.7	60.3	92.6	-	-
Total Crash Rate	81.3	91.2	147.2	-	-
Crash Severity Rate (12:3:1)	201.8	161.8	261.7	40.0	n/a

Several notes must be made regarding the presented crash rates. First, many confounding factors influence crash rates and simply improving or upgrading a roadway is no guarantee that potential crash reduction numbers will be realized. Higher truck volumes, or even higher volumes of other vehicles, on the new roadway could reduce the projected safety benefits, for example. Additionally, because the proposed U.S. 460 expressway would include a new interchange at either end, it is worth noting that interchanges often include higher incident rates due to factors like merges, curves, and slowing traffic; thus, while the roadway itself may see reduced crash numbers, the new interchanges may experience a higher number of crashes than before. Finally, a major assumption has been made regarding truck volumes in that trucks in particular would shift from the old highway onto the new tolled expressway, thus transferring truck crashes to the new expressway from the existing alignment.

5.3.3 Calculating U.S. 460 Economic Hindrance

The calculated values of excess trucking costs can be used in the derived inoperability input-output model to determine a value of economic hindrance caused to other industries due to excess trucking costs incurred by the trucking sector. Note that this value clearly should not be used in conjunction with the first economic metric calculated, as it would be double counting.

The calculated consequences of the economic hindrance incurred by an excess trucking cost based on travel time savings of $52,000 per day and truck fatality crash savings of $43,400 per day to the trucking sector are shown in Table 15 below. This value is calculated by simply multiplying the individual excess trucking costs calculated above with the BEA dollar loss ratio calculated previously in the inoperability input-output model and presented again in Table 15. Note that for the trucking sector, the model shows a loss of 114%, however in order to not double count, only a value of 14% is shown, because the remaining 100% is already tabulated as the excess trucking cost above.

Thus, it is shown that current mobility constraints on U.S. 460 cause additional economic hindrances of approximately $55,000 per day, totaling over $20 million annually to industry, which has the potential to be reduced or eliminated with the construction of the U.S. 460 expressway, depending on the amount of the toll that is charged. Additionally, about $46,000 per day, or $16.8 million per year, in excess trucking costs due to truck fatality crashes in the U.S. 460 study corridor might be reduced if the interstate-grade U.S. 460 expressway were constructed.

Table 15: Economic hindrance by industry based on calculated excess trucking costs to the trucking sector on U.S 460

BEA Industry Labels (Input-Output Model)	BEA $ loss, ratio	Daily Economic Hindrance, $ Mobility (travel time)	Daily Economic Hindrance, $ Safety (truck crashes)
Truck transportation	1.1428	7423	6195
Petroleum and coal products	0.1169	6080	5075
Oil and gas extraction	0.0952	4951	4132
Wholesale trade	0.0661	3436	2867
Motor vehicles, bodies and trailers, and parts	0.0364	1892	1579
Warehousing and storage	0.0240	1249	1042
Chemical products	0.0237	1232	1029
Fabricated metal products	0.0184	959	800
Retail trade	0.0177	919	767
Plastics and rubber products	0.0172	892	745
Primary metals	0.0154	802	670
Utilities	0.0100	520	434
Computer systems design and related services	0.0090	466	389
Information and data processing services	0.0089	462	385
Machinery	0.0070	364	303
Computer and electronic products	0.0066	346	288
Electrical equipment, appliances, and components	0.0064	335	280
Paper products	0.0063	328	274
Waste management and remediation services	0.0058	300	251
Publishing industries (includes software)	0.0055	286	238
Construction	0.0052	272	227
Printing and related support activities	0.0040	208	174
Food services and drinking places	0.0036	189	158
Nonmetallic mineral products	0.0028	144	120
Support activities for mining	0.0026	133	111
Mining, except oil and gas	0.0025	127	106
Food and beverage and tobacco products	0.0023	121	101
Wood products	0.0021	111	92
Miscellaneous manufacturing	0.0016	82	68
Farms	0.0015	80	67
Textile mills and textile product mills	0.0015	78	65
Forestry, fishing, and related activities	0.0012	61	51
Other transportation equipment	0.0011	59	49
Furniture and related products	0.0005	25	21
Apparel and leather and allied products	0.0005	24	20
Other (services, government, etc.)	varies	20,168	16,831
	Daily Total	55,125	46,005
	Daily Total per Mile	1103	920
	Annual Total	20,120,618	16,791,749

5.3.4 Summary of U.S. 460 Findings

A summary of the values for U.S. 460 expressway proof of concept presented in the tables above is given below in Table 16, many of which will be presented later in the 5.5 Decision Model section.

Table 16: Summary Table of U.S. 460 Measures

<table>
<tr><td rowspan="2">Corridor Metrics</td><td colspan="2">Length of Corridor, miles</td><td>50</td></tr>
<tr><td colspan="2">AADTT, daily trucks</td><td>2377</td></tr>
<tr><td rowspan="4">Travel Time Savings, minutes</td><td colspan="2">For Corridor Length per Truck</td><td>13</td></tr>
<tr><td colspan="2">Per Truck Per Mile</td><td>0.26</td></tr>
<tr><td colspan="2">Annual Savings, Entire Corridor</td><td>30,900</td></tr>
<tr><td colspan="2">Annual Savings Per Mile</td><td>618</td></tr>
<tr><td rowspan="3">Truck Crash Severity 2005-2010 (12:3:1)</td><td colspan="2">Rate per 100 million VMT</td><td>201.8</td></tr>
<tr><td colspan="2">Rate Difference with Improvement</td><td>40</td></tr>
<tr><td colspan="2">Annual Reduction per Mile (Rate*VMT / 50)</td><td>0.35</td></tr>
<tr><td rowspan="7">Proposed Economic Metrics</td><td colspan="2">Economic Importance</td><td>3.56</td></tr>
<tr><td rowspan="4">Excess Trucking Cost, $</td><td>Mobility - daily</td><td>52,000</td></tr>
<tr><td>Mobility – daily per mile</td><td>1040</td></tr>
<tr><td>Safety - daily</td><td>43,400</td></tr>
<tr><td>Safety – daily per mile</td><td>868</td></tr>
<tr><td rowspan="2">Daily Economic Hindrance per mile, $</td><td>Mobility</td><td>1103</td></tr>
<tr><td>Safety</td><td>920</td></tr>
</table>

5.4 Proof of Concept #2: U.S. 29 Bypass – Charlottesville / Albemarle County, VA

The U.S. 29 corridor serves central Virginia and north-central North Carolina from the Washington, DC metropolitan area south to Greensboro, North Carolina via Gainesville, Warrenton, Culpeper, Charlottesville, Lynchburg, and Danville, Virginia. Between I-66 in Northern Virginia and Greensboro, North Carolina, the U.S. 29 corridor is, at a minimum, a four-lane divided highway with numerous at-grade crossings, many of which are signalized. For longer distance trips, truckers might conceivably select roughly parallel Interstate 81 and U.S. 220 or Interstate 85 and Interstate 95 for a higher level of service route, as depicted in Figure 7. However, approximately 67% of tonnage on the U.S. 29 corridor in Virginia is pass-through freight (Cambridge Systematics, 2010).

Regionally in central Virginia, there is much debate on whether stoplights on the U.S. 29 corridor, specifically a segment with a reduced speed of 45 mile per hour and a sequence of 13 traffic lights just north of Charlottesville impede mobility such that they serve as a bottleneck to reduce economic activity in Lynchburg and Danville with the Northeast Corridor, i.e., Washington, DC; New York City; etc., and thus hinder economic growth in that area of southern Virginia. As a result, a 6.2-mile bypass is proposed for construction north of Charlottesville in Albemarle County as an alternate route to avoid this heavily commercially developed area (VDOT, 2012-d).

5.4.1 Calculating U.S. 29 Economic Importance

Estimates of freight tonnage carried on the U.S. 29 corridor was performed slightly differently than for the U.S. 460 corridor, in part to demonstrate alternate methods, but also because of the difference in alignment of the corridors. First, as above, FAF region groupings were developed, given the directionality of U.S. 29 and natural flow for traffic from northeast to the south and west, as well as the positioning of other parallel routes. Unlike the U.S. 460 case study in which routes are less parallel and branch out in different directions, the U.S. 29 corridor has a number of parallel corridors that serve similar FAF region origins and destinations (e.g., I-81, I-95, and connecting routes such as U.S. 220 and I-85, respectively), as shown in Figure 7. Thus, route assignment based on origin-destination regions, even those that are the size of the FAF regions, are much more difficult for this corridor.

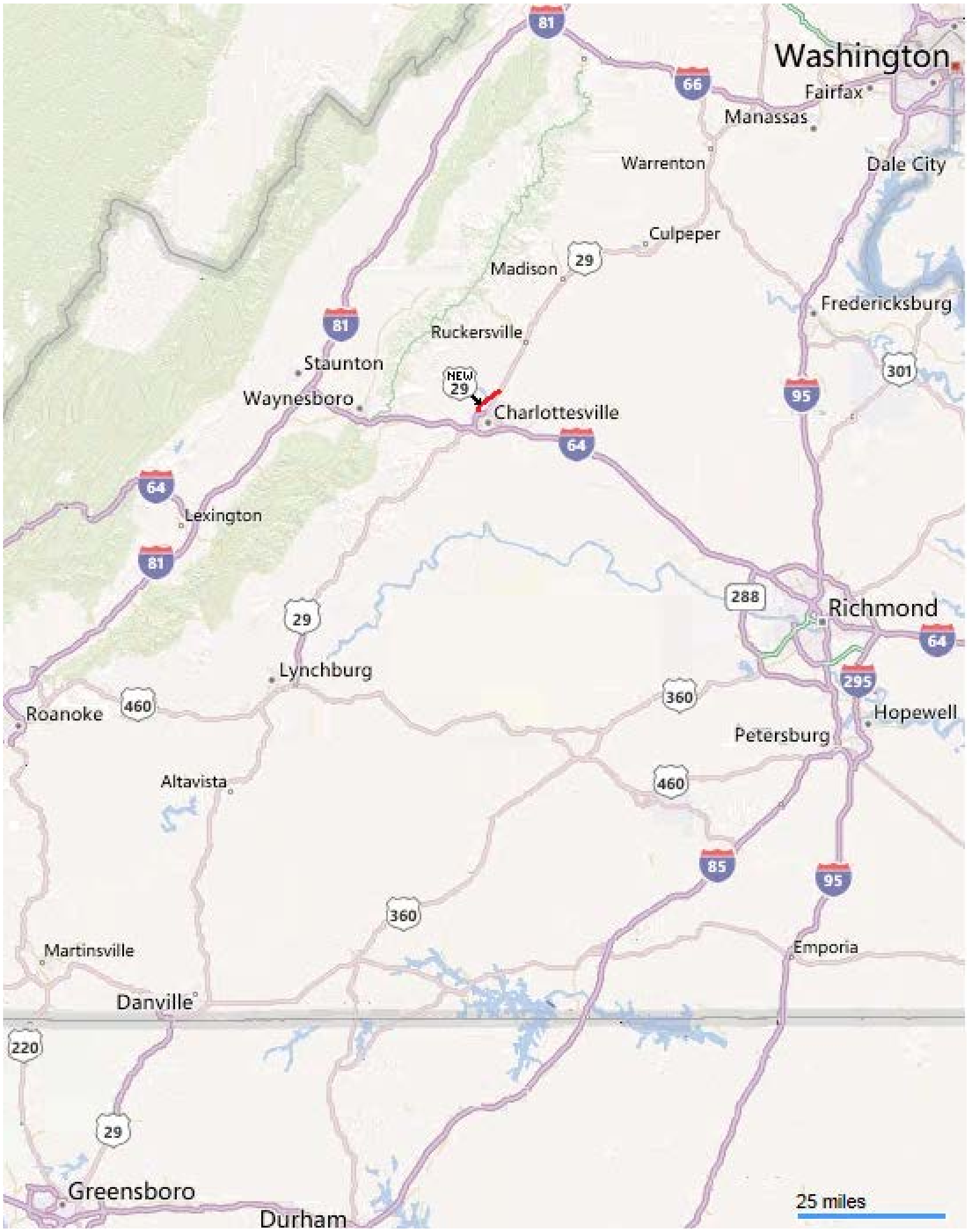


Figure 7: Map of U.S. 29 corridor with proposed bypass and other major alternate routes

Commodity flows through the region were determined using BEA data. Origins and destinations of commodity flows were sorted into several main groups: the Northeast, where traffic is funneled through or around Washington, DC for points to or from the south and west; Virginia, which includes the Remainder of Virginia FAF region around Charlottesville; a South region; and a West region that is conceivably connected to the U.S. 29 corridor via I-64 at Charlottesville. A final group, the Northwest region, was discarded from analysis, since the U.S. 29 corridor seems to be an unlikely route given its directionality. These groupings are shown in Figure 8 with the Interstate Highway System to show connections from the U.S. 29 corridor to these regions.

Using a screenline across central Virginia, 2007 AADTT volumes were taken from the FAF for I-81, the U.S. 29 bypass segment, and I-95. These AADTT volumes were used to assign tonnage values for each corridor. Specifically, approximately 1744 trucks per day travel on the U.S. 29 corridor segment of the proposed bypass, while AADTT for I-95 and I-81 are 15,000 and 12,000 trucks, respectively, as shown in Table 17. Thus, approximately 6% of the total tonnage of selected commodities were assigned to the U.S. 29 corridor. The values generated from the inoperability input-output model are applied to this commodity tonnage to provide a value of economic importance, which is also shown in Table 17; as shown in bold text, the value of economic importance for the U.S. 29 corridor is 16.43. In this proof of concept, because the regional origin-destination groups are the same for all three corridors, the value of economic importance will be exactly proportional to the AADTT volumes for the three corridors.

It is possible that a new, improved U.S. 29 bypass will alleviate a bottleneck in the regions such that it would not only serve existing U.S. 29 truck traffic on the existing route, but also attract truck traffic from other, more congested neighboring routes I-81, for example. Additionally, the cities of Lynchburg and Danville could benefit from new industry with this improved connection to markets in the north. All of these possibilities would increase truck volumes on U.S. 29, and thus potentially provide added significance to the corridor and benefit to the trucking industry. However, for the purposes of this proof of concept, only existing truck volumes were analyzed.

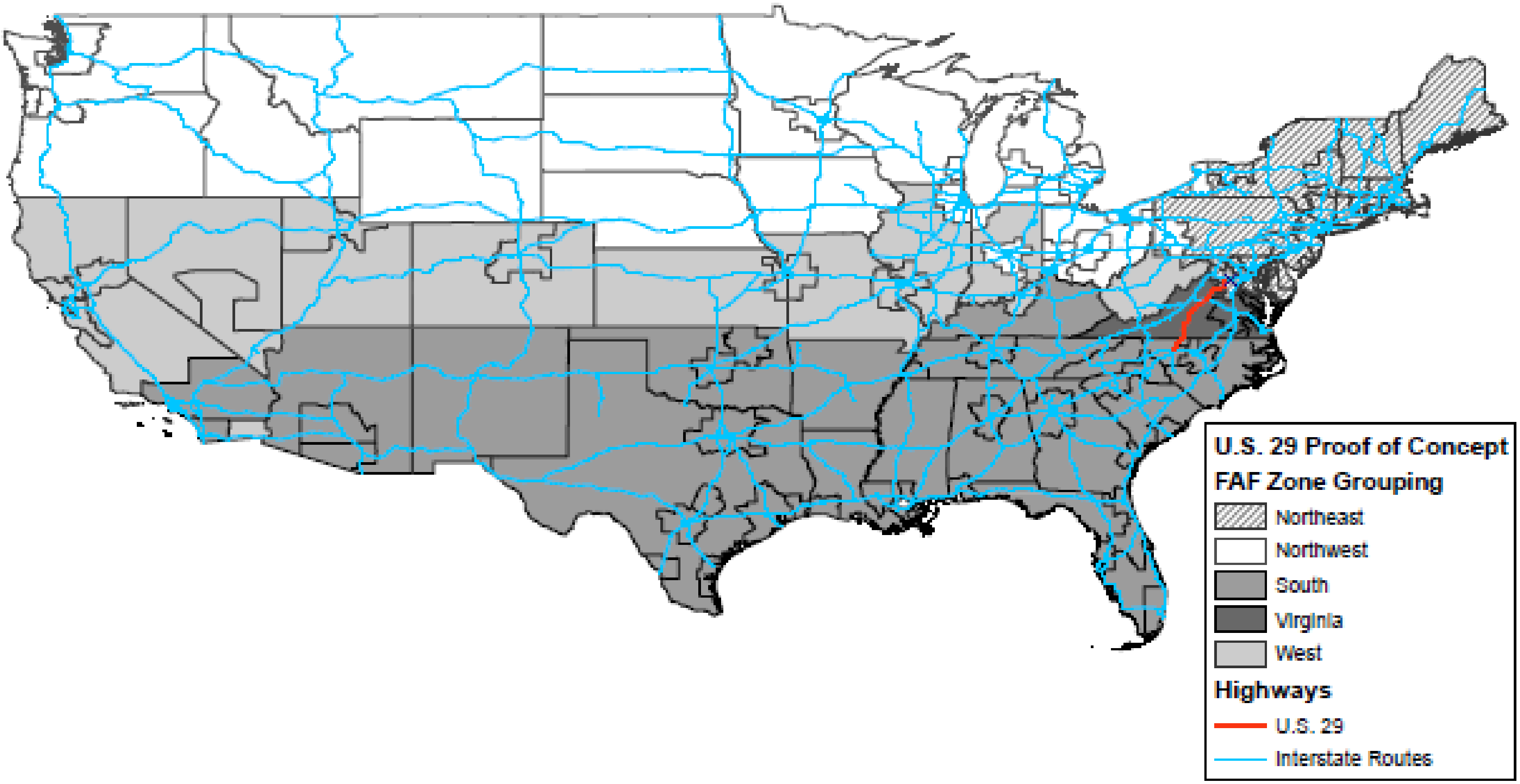


Figure 8: FAF region groupings for origin-destination route assignment designation through central Virginia

Table 17: Total Commodity Tonnage by Route for U.S. 29 Proof of Concept

Commodity	Kilotons by route for Proof of Concept				Input-Output Economic Importance by route for Proof of Concept		
	Total	US 29	I-95	I-81	US 29	I-95	I-81
Cereal Grains	18334	1112	9567	7654	2.15	18.48	14.78
Meat/Seafood	7947	482	4147	3318	0.93	8.01	6.41
Milled grain prods.	5421	329	2829	2263	0.64	5.46	4.37
Other foodstuffs	25754	1563	13440	10752	3.02	25.96	20.76
Building Stone	714	43	373	298	0.11	0.94	0.75
Gravel	30442	1847	15886	12709	4.63	39.85	31.88
Natural sands	1937	118	1011	809	0.29	2.54	2.03
Nonmetallic minerals	10524	639	5492	4394	1.60	13.78	11.02
Logs	14873	902	7761	6209	1.49	12.84	10.27
Wood Prods.	19758	1199	10311	8248	1.57	13.46	10.77
Total	135703	8234	70817	56653	**16.43**	141.30	113.04
AADTT	28744	1744	15000	12000			
Percentage of total	100	6	52	42			

5.4.2 Calculating U.S. 29 Excess Trucking Costs

Excess trucking costs calculated for mobility and safety are calculated for this proof of concept based on travel time savings and potential truck crash reduction for a scenario comparing the existing U.S. 29 with the projected benefits of a completed U.S. 29 bypass.

A conservative estimate of total excess trucking costs can be derived using 2007 AADTT and truck speed values from the FAF. The value of commercial vehicle time used to calculate excess costs is $105.67 as reported in TTI’s Urban Mobility Report (Schrank et al., 2010). Given 2007 truck speeds on the existing U.S. 29 corridor is 47.3 miles per hour, and will be compared to an estimated truck speed for the new bypass of 55 miles per hour, the expected posted speed limit. It should be noted that the former value is likely high considering the speed limit of the existing U.S. 29 is only 45 miles per hour, and there is great likelihood of truck traffic being further hindered by traffic lights; however, this value, as given by the FAF will be used for consistency, and provide a conservative estimate. The difference in current and new truck speeds result in a travel time savings of 0.7 minutes per truck. With a 2007 AADTT of 1744 trucks per day, this results in 20 hours of delay and excess trucking costs per day of $2150, or $785,000 per year.

Excess trucking costs can similarly be calculated from other measures, such as projected safety benefits. Crash data on a compact disc (CD) for the entire state of Virginia for 2005-2010 were obtained directly from the VDOT Central Office, by request. Crash data on this CD were organized in a series of tables. In order to glean relevant truck crash data specifically for the U.S. 29 study corridor, two tables (i.e., "crash document" and "crash vehicle") had to be joined by the crash document number. Several filters were applied to this data. Data were limited to crashes that:

- Include vehicle classes that identify trucks;
- Occurred on U.S. 29; and
- Occurred between Latitude/Longitude points of either end of the study area (38.057148,-78.495598 and 38.112477,-78.453026), or
- Occurred between state designated mileposts of the study area (139.404 to 143.417).

Note that both latitude/longitude coordinates and mileposts were used to locate relevant crash data since neither of these fields was consistently completed for all crash data for all years. This raw crash data for the U.S. 29 study corridor is presented in Table C-2 of Appendix C. The filtered crash data relevant to the U.S. 29 study corridor for years 2005-2010 is presented in Table 18.

Table 18: 2005-2010 Truck Crashes by Crash Type on U.S. 29 Study Corridor

	Truck Crashes on U.S. 29 Study Corridor						
Crash Type	2005	2006	2007	2008	2009	2010	2005-2010 Average
Fatal Crash	0	0	0	0	0	0	0.0
Persons Killed	0	0	0	0	0	0	0.0
Injury Crash	8	5	1	3	3	3	3.8
Persons Injured	14	5	2	4	5	5	5.8
PDO Crash	11	9	11	16	12	22	13.5
Total Crash	19	14	12	19	15	25	17.3
Crash Severity Number (12:3:1)	35	24	14	25	21	31	25.0

To normalize the data, the distance of the existing segment to be replaced was determined to be 4 miles based on the farthest endpoints of crash data. The 2007 AADTT of the existing segment was gathered for the study corridor segment from the FAF and converted to a daily truck VMT of 6976 for the total length of the study corridor. This value was multiplied by 365 to get annual truck VMT. These values are presented in Table 19.

Table 19: Measures used for Safety Calculations for U.S. 29 Study Corridor

Measures	U.S. 29 Study Corridor
Distance	4 miles
FAF AADTT 2007	1744 vehicles
Daily Truck VMT	6976
Total Annual Truck VMT (x100 million)	0.025462

Truck crash rates for the U.S. 29 corridor were derived simply by dividing values presented in Table 18 by the value for total annual truck VMT presented in Table 19.

The calculated truck crash rates for the years 2005-2010 by crash type for the U.S. 460 study corridor are presented in Table 20.

Table 20: 2005-2010 Truck Crash Rates by Crash Type on U.S. 29 Study Corridor

Crash rates per 100 million Truck VMT	Truck Crash Rates on U.S. 29 Study Corridor						
	2005	2006	2007	2008	2009	2010	2005-2010 Average
Fatal Crash Rate	0	0	0	0	0	0	0
Persons Killed Rate	0	0	0	0	0	0	0
Injury Crash Rate	314.2	196.4	39.3	117.8	117.8	117.8	150.5
Persons Injured Rate	549.8	196.4	78.5	157.1	196.4	196.4	229.1
PDO Crash Rate	432.0	353.5	432.0	628.4	471.3	864.0	530.2
Total Crash Rate	746.2	549.8	471.3	746.2	589.1	981.8	680.7
Crash Severity Rate (12:3:1)	1374.6	942.6	549.8	981.8	824.7	1217.5	981.8

Compared with truck crash rates on other Virginia Primary Roadways that were presented in Table 7, only the average truck fatality crash and persons killed rates are lower on the U.S. 29 study corridor, with zero fatal crashes recorded for the six years presented. Similarly, when compared with crash rates on the Virginia interstate highways in Table 7, which have similar characteristics as the proposed U.S. 29 bypass, only average truck fatality crash and person killed rates on the existing roadway is lower. In fact, perhaps due to the more urban nature of the U.S. 29 corridor with slower speeds and frequent traffic signals, the truck crash rate is notably higher than the state average for other primary roadways. These comparisons are presented in Table 21 below.

The difference between the current and interstate-grade proposed expressway are presented for injury, PDO, and total crash rates and persons injured, alongside the potential annual reduction in the number of these crashes and persons injured, given the existing truck VMT in the study corridor. Using a value of $331,108 given by the Federal Motor Carrier Safety Administration (FMCSA, 2008) as the average cost of each injury crash involving a medium/heavy vehicle, it can be estimated by multiplying with the potential 3.1 crashes reduced that over $1 million in annual excess trucking costs (or $2800 per day) can be potentially eliminated with the construction of the proposed U.S. 29 bypass. Likewise, FMCSA (2008) gives a value of $148,279 as the average cost for a truck-involved crash for all medium/heavy vehicles. From this, it can be estimated by multiplying with the potential 12 crashes reduced that about $1.8 million in annual excess trucking costs (or $4900 per day) can be potentially eliminated with the construction of the proposed U.S. 29 bypass.

Table 21: Comparison of Average Crash Rates for U.S. 29 Study Corridor to All Virginia Primary and Interstate Roadways

Average Annual Virginia Truck Crash Rates per 100 million Truck VMT					Potential Annual Crash Reduction
Truck Crash Rate Type	U.S. 29 Study Corridor 2005-2010	Interstate System 2005-2007	Primary Roadways 2005-2007	U.S. 29 to Interstate System Difference	
Fatal Crash Rate	0.0	1.0	2.9	-	-
Persons Killed Rate	0.0	1.1	3.4	-	-
Injury Crash Rate	150.5	30.0	51.6	120.6	3.1
Persons Injured Rate	229.1	44.4	74.0	184.7	4.7
PDO Crash Rate	530.2	60.3	92.6	469.9	12.0
Total Crash Rate	680.7	91.2	147.2	589.5	15.0
Crash Severity Rate (12:3:1)	981.8	161.8	261.7	820.1	n/a

5.4.3 Calculating U.S. 29 Economic Hindrance

The calculated values of excess trucking costs can be used in the derived inoperability input-output model to determine a value of economic hindrance caused to other industries due to excess trucking costs incurred by the trucking sector. Note, this value clearly should not be used in conjunction with the first value calculated, as it would be double counting.

The calculated consequences of the economic hindrance incurred by an excess trucking cost based on travel time savings of $2150 per day and truck fatality crash savings of $7700 per day to the trucking sector are shown in Table 22 below. This value is calculated by simply multiplying the individual excess trucking costs calculated above with the BEA dollar loss ratio calculated previously and presented again in Table 22. Note that for the trucking sector, the model shows a loss of 114%, however in order to not double count, only a value of 14% is shown, since the remaining 100% is already tabulated above as the excess trucking cost.

Thus, it is shown that current mobility constraints on U.S. 29 cause additional economic hindrances of nearly $2300 per day, totaling over $830,000 annually to industry, which has the potential to be reduced or eliminated with the construction of the U.S. 29 bypass. Additionally, over $8100 per day, or almost $3 million per year, in excess trucking costs due to truck crashes in the U.S. 29 study corridor might be reduced if the interstate-grade U.S. 29 bypass were constructed.

Table 22: Economic hindrance by industry based on calculated mobility-based excess trucking costs to the trucking sector on U.S. 29

BEA Industry Labels (Input-Output Model)	BEA $ loss, ratio	Daily Economic Hindrance, $	
		Mobility (travel time)	Safety (truck crashes)
Truck transportation	1.1428	307	1097
Petroleum and coal products	0.1169	251	899
Oil and gas extraction	0.0952	205	732
Wholesale trade	0.0661	142	508
Motor vehicles, bodies and trailers, and parts	0.0364	78	280
Warehousing and storage	0.0240	52	185
Chemical products	0.0237	51	182
Fabricated metal products	0.0184	40	142
Retail trade	0.0177	38	136
Plastics and rubber products	0.0172	37	132
Primary metals	0.0154	33	119
Utilities	0.0100	21	77
Computer systems design and related services	0.0090	19	69
Information and data processing services	0.0089	19	68
Machinery	0.0070	15	54
Computer and electronic products	0.0066	14	51
Electrical equipment, appliances, and components	0.0064	14	50
Paper products	0.0063	14	49
Waste management and remediation services	0.0058	12	44
Publishing industries (includes software)	0.0055	12	42
Construction	0.0052	11	40
Printing and related support activities	0.0040	9	31
Food services and drinking places	0.0036	8	28
Nonmetallic mineral products	0.0028	6	21
Support activities for mining	0.0026	6	20
Mining, except oil and gas	0.0025	5	19
Food and beverage and tobacco products	0.0023	5	18
Wood products	0.0021	5	16
Miscellaneous manufacturing	0.0016	3	12
Farms	0.0015	3	12
Textile mills and textile product mills	0.0015	3	12
Forestry, fishing, and related activities	0.0012	3	9
Other transportation equipment	0.0011	2	9
Furniture and related products	0.0005	1	4
Apparel and leather and allied products	0.0005	1	4
Other (services, government, etc.)	varies	834	2981
Daily Total		2279	8149
Daily Total per Mile		570	2037
Annual Total		831,958	2,974,252

Several notes must be made regarding the presented crash rates. First, many factors influence crash rates and simply improving or upgrading a roadway is no guarantee that potential crash reduction numbers will be realized. Higher truck volumes, or even higher volumes of other vehicles, on the new roadway could reduce the projected safety benefits, for example. Additionally, because the proposed U.S. 29 bypass would include a new interchange at either end, including one involving a stop light with a left turn for through traffic, it is worth noting that interchanges often include higher incident rates due factors like merges, curves, and slowing traffic; thus, while the roadway itself may see reduced crash numbers, the new interchanges may experience a higher number of crashes than the old alignment. At the same time, other programmed projects, such as that which involves adding a second lane to the southbound U.S. 29 on-ramp at the junction with U.S. 250, could potentially achieve similar safety benefits, which would necessarily be included in the final decision model for Finally, because the existing U.S. 29 corridor has numerous businesses, many trucks will likely still travel on the existing roadway, thus reducing the full projected benefits for potential reduction of truck crashes of the proposed U.S. 29 bypass.

5.4.4 Summary of U.S. 29 Findings

A summary of the values for the U.S. 29 bypass proof of concept presented in the tables above is given below in Table 23, many of which will be used in the 5.5 Decision Model section.

Table 23: Summary Table of U.S. 29 Measures

Corridor Metrics	Length of Corridor, miles		4
	AADTT, daily trucks		1744
Travel Time Savings, minutes	For Corridor Length per Truck		0.71
	Per Truck Per Mile		0.18
	Annual Savings, Entire Corridor		1238
	Annual Savings Per Mile		310
Truck Crash Severity 2005-2010 (12:3:1)	Rate per 100 million VMT		981.8
	Rate Difference with Improvement		820
	Annual Reduction per Mile (Rate*Truck VMT/4)		5.23
Proposed Economic Metrics	Economic Importance		16.43
	Excess Trucking Cost, $	Mobility – daily	2150
		Mobility – daily per mile	538
		Safety – daily	7700
		Safety – daily per mile	1925
	Daily Economic Hindrance per mile, $	Mobility	570
		Safety	2037

5.5 Decision Model

A summary of the key metrics calculated and derived for both the U.S. 460 expressway and U.S. 29 bypass proofs of concept above are presented in Table 24. Despite only two corridors to compare, several simple decision models could be employed to rank the corridors for their relative benefits and thus prioritize the improvements. These decision models could also be used to compare a larger number of corridors, if scores were proportionately given to each metric between a range of zero to five, for example.

For this comparison, the first decision model will use equal weightings for all metrics, the second will emphasize safety metrics at a scale of 2:1, and the final will emphasize mobility measures also using a scale of 2:1. The outcomes of these decision models are presented in Table 25 below. To avoid double counting, the economic importance metric will not be used in any of the decision models.

Table 24: Comparison of Key Metrics for U.S. 460 and U.S. 29 Study Corridors

Metric			Corridor Improvement	
			U.S. 460	U.S. 29
Travel Time Savings	Per Truck Per Mile		0.26	0.18
	Annual Savings Per Mile		618	314
Truck Crash Severity 2005-2010 (12:3:1)	Rate per 100 million VMT		201.8	981.8
	Annual Reduction per Mile		0.35	5.23
Proposed Economic Metrics	Economic Importance		3.56	16.43
	Daily Excess Trucking Cost per mile, $	Mobility	1040	538
		Safety	868	1925
	Daily Economic Hindrance per mile, $	Mobility	1103	570
		Safety	920	2037

Table 25: Several decision model approaches to prioritize improvements

Metric			Equal Weighting		Weighting Emphasizes Safety		Weighting Emphasizes Mobility	
			U.S. 460	U.S. 29	U.S. 460	U.S. 29	U.S. 460	U.S. 29
Travel Time Savings	Per Truck Per Mile		1	0	1	0	2	0
	Annual Savings Per Mile		1	0	1	0	2	0
Truck Crash Severity 2005-2010 (12:3:1)	Rate per 100 million VMT		0	1	0	2	0	1
	Annual Reduction per Mile		0	1	0	2	0	1
Proposed Economic Metrics	Daily Excess Trucking Cost per mile, $	Mobility	1	0	1	0	2	0
		Safety	0	1	0	2	0	1
	Daily Economic Hindrance per mile, $	Mobility	1	0	1	0	2	0
		Safety	0	1	0	2	0	1
Total Score:			**4**	**4**	4	**8**	**8**	4

As Table 25 shows, of the two corridors being compared, the U.S. 460 corridor improvement provides greater mobility benefits while the U.S. 29 corridor improvement provides greater safety benefits. When all metrics employed here are taken equally, the two corridors have a tied score. However, this outcome is less likely given more corridor improvements to score proportionately for each metric on a scale of zero to five, for example, and an increased number of measures that would come from the Virginia Statewide Performance System to round out the freight module.

Additionally, instead of presenting the proposed economic metrics as a ranking, because the units are normalized per mile and have a dollar value, the actual dollar value from these metrics could be summed and used for prioritizing the proposed improvements: the daily mobility and safety excess trucking costs per mile and economic hindrance per mile. This value could be used for a multitude of reasons, including in the event of a tie between several alternatives, as was the case with an equal weighting. In this case, the daily economic benefit derived per mile from improving the U.S. 460 and U.S. 29 corridors totals $3931 and $5070, respectively.

TASK 6 – CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

The developed freight infrastructure framework will be a tool for planners at state DOTs, MPOs, and even FHWA to consider economic importance of freight corridors and needs of the trucking industry to maintain a strong economy and smooth flow of goods. This tool may be used alongside existing prioritization frameworks and selectively implemented, if preferred. This freight infrastructure prioritization framework will fill gaps that currently exist in most asset management strategies by focusing on freight performance and economic importance of selected corridors. The freight sector plays an important role in the economy and needs a reliable highway network, yet the needs of the freight sector are often overlooked by asset management programs when allocating infrastructure improvement funding.

The methodology developed here uses existing, easily obtained data sources for the development of the framework, understanding the already limited resources of transportation departments. The Bureau of Economic Analysis' input-output model and Federal Highway Administration's Freight Analysis Framework both contain a rich and robust data set that can be used to examine any part of the country. The developed framework tools also maintain flexibility for the user to manipulate the framework to meet various agency goals to generate a list of prioritized infrastructure needs.

The proof of concept developed here demonstrated how the framework can be applied to a given scenario. In practice, all commodities from the input-output model and Freight Analysis Framework would be applied, but for sake of space and time, a limited number of commodities were selected for demonstration.

As seen in Table 10, the metric of economic importance of commodities showed little proportional difference to the basic sum of kilotons carried on the routes or AADTT. In other words, despite a potentially laborious process to develop route assignments for commodities to and from given regions, the results may not differ that much from data already given by AADTT in the Freight Analysis Framework. This suggests that the commodities that will most impact the framework will be those that have a particularly high economic importance to the region or are of otherwise distinct regional significance.

This said, it is believed that using the second and third metrics (excess trucking cost and economic hindrance) together instead of the first metric (economic importance) may be a fuller depiction of the economic situation. In this way, a more common metric, excess trucking costs, which is relatively easy to develop for a variety of issues related to mobility, pavement condition, safety, etc., can be further extrapolated to present a fuller economic impact of the highway's deficiencies.

6.2 Recommendations

Numerous recommendations can be drawn from this research. The first and foremost recommendation is an appeal to highway agencies to include freight metrics in asset management programs. Freight plays a significant role in the national, state, and local economies and is highly dependent on the provision of a reliable highway network for success. This research highlights and has developed numerous freight-based performance measures that might be included into asset management programs.

As to the methodology and developed economic metrics presented herein, there is a recommendation for future research. In order to verify, validate, and establish any new performance measures, specifically the freight economic metrics developed here, additional case studies need to be developed to demonstrate this framework. Further calibration and sensitivity analyses need to be conducted as well. Finally, any well-tested metric will need to be linked with existing state asset management systems, which may require further testing, calibration, and demonstration.

6.3 Justification for Funding Freight Highway Infrastructure

The implementation of a dedicated freight highway asset management system could lead to increased trucking industry support for providing funding for infrastructure projects. This freight-focused asset management system would enable the public sector to view the highway system from the freight perspective, and reach out to the trucking industry. By showing the benefits and savings the trucking industry could derive from the prioritized infrastructure improvements, there might be increased support for public-private partnerships. Alternatively, a variety of road user fee strategies focused on freight could be justified with this freight module in place to apply funds to prioritized projects that would address freight highway needs. These strategies include a variety of truck vehicle-miles travelled fee approaches

There are many different objectives for implementing a road user fee system, including replacement of the fuel tax, congestion-based and demand management, environmental, facility-based revenue generation, and supplemental revenue generation. In particular, as shown in Table 26, several Central European countries and New Zealand impose tolls on heavy goods vehicles (HGV), i.e., trucks, in an effort to collect sufficient fees to be proportional with the costs that trucks impose on the highway infrastructure. In these existing systems, the proportional costs for highway wear and tear are measured by the number of axles or maximum laden weight. The motivation behind the implementation of most of these systems relates to increases in truck traffic in conjunction with funding shortfalls compared to the backlog of highway infrastructure needs.

Table 26. Existing truck-based road user fee deployments and characteristics

Country and Truck-based Road User Fee System	Tolled Roadways		Per-mile Fee Basis				
	Specific	All	Number of Axles	Emissions Class	Roadway Classification	Maximum Laden Weight	Location
Germany, HGV Tolling	X		X	X			
Austria, GO-Maut (HGV Tolling)	X		X				
Czech Republic, Truck Tolling	X		X	X			
Slovak Republic, Truck Tolling	X		X	X	X		
Switzerland, Heavy Vehicle Fee		X		X		X	
New Zealand, EROAD		X				X	X

Notes of interest for each of the various systems include:

- Germany: tolls range from €0.09 to €0.14 per kilometer (US $0.23 to US $0.35 per mile) and fund transportation problems; gross revenue in 2009 was about €3.9 billion (US $5 billion).
- Austria: revenues from the system are earmarked for use on the charged roadway network, which does not receive funding from general revenues.
- Czech Republic: a primary objective of the system is to capture revenues from foreign vehicles that were not viewed as fully contributing to the funding system; the system generated about US $340 million in 2008.
- Slovak Republic: a relatively newer system than those in neighboring countries, this system started in 2010, and generated an estimated $11.6 million in the first month of operation.
- Switzerland: with a foundation of freight pricing going back to 1983, the current program was implemented in 2001.
- New Zealand: this high technology deployment is touted as the "world's first network-wide autonomous Global Navigation Satellite System (GNSS) and cellular tolling system for heavy goods vehicles (HGV's)" (Bradley, 2011).

All of these systems serve as a model for a truck-based road user fee deployment in the United States that could assess and collect supplemental revenue for the purposes of funding prioritized freight highway infrastructure needs. Certainly, other mechanisms could also be employed, such as dedicated use of fuel taxes or licensing and registration fees that are assessed on trucks. Public private partnerships with the trucking industry might also be a possibility, although due to the vast number of stakeholders and independent operators, it would likely be overly difficult to be fair and reach consensus.

In conclusion, following the implementation of an asset management system that prioritizes freight highway infrastructure needs, dedicated revenue to fund these needs is required. Supplemental revenue assessed on trucks based on vehicle-miles traveled is one tested approach to accomplish this objective. Additional information will be presented in Project B.

PROJECT B METHODOLOGY: A MARKET BASED FRAMEWORK FOR INFRASTRUCTURE MANAGEMENT

TASK 1 – LITERATURE REVIEW

1.1 Shale Gas Infrastructure and Production Planning

The Marcellus shale, a layer of shale rock beneath the rolling hills and mountains of Pennsylvania, is the largest unconventional natural gas reserve in the world. This well-known geological formation that contains significant amounts of natural gas was never considered worthwhile until recent technology advances. Though reserve estimates are considered uncertain at this point, most of the completed Marcellus well revealed abundant recoverable reserves. Together with the emphasis on consuming green energy due to environmental issues, natural gas, which has considerably lower carbon content than petroleum and coal, will no doubt grasp its own share of the market.

Marcellus shale gas play becomes more and more attractive these days as the drilling technology advances. Reports show that the activity in the Marcellus will continue to expand and natural gas production from Marcellus could rise to almost 4 billion cubic feet BCF per day by 2020 (Considine and Watson 2009). However, among some key factors affecting development is infrastructure and production planning. Though it may seem hard to explore and drill for natural gas, the real work happens to be the development of a network consisting of thousands of miles of gathering lines and pipelines to carry the gas to consumers (Considine et al. 2010). Besides, building natural gas processing facilities takes considerable time and incurs significant costs. To sum up, developing transportation and production processing networks takes money and time. But the high potential environment and investment impact stimulates the research.

One of the most major concerns is that the decision maker is exposed to a great deal of uncertainty. Though the location of gas fields could be identified, the amount of gas in these reserves remains uncertain until the platform is built. Therefore, it is crucial to take uncertainties into account when formulating the model.

A typical shale gas infrastructure and production problem has multiple potential reserves within a region to build well platforms on. The extracted natural gas needed to be purged and dried before sold to merchants and customers for use. Therefore, a production platform is usually built on site to process the gas before it can be transported to other areas. In this report, we call the combo of well platform and production platform 'a platform' in general. After the gas is processed on site, it is transported via pipelines that connecting platforms together. All the gas produced is to transport to a central pipeline that connects different regions together. The shale gas infrastructure and production planning problem requires the decision maker to select when and where to build platforms, to increase the capacity of platforms and to install pipelines. Besides, operation decisions are to be made to determine the production schedule for different gas fields.

For simplification, the planning horizon is discretized into time periods. The decision maker is to make decision at the beginning of each time period and all the decision take immediate effect. As the decisions regarding when and where to build platforms and pipelines are represented as binary variables, and other decisions including the capacity expansion and extraction schedule are real-valued, the formulation has the form of mixed binary integer programming. However, all the decision variables are dependent on the information of gas reserves. The problem thus becomes a stochastic programming with endogenous uncertainties. In Task 2, we will present both a one-stage and a multi-stage stochastic programming model for the shale gas infrastructure and production planning.

1.1.1 Economic Impact

The economic impact of shale gas is studied by Considine et al. (2009, 2010). They use IMPLAN modeling system to estimate the job creation, value added, etc. However, the development of the shale gas network consisting of thousands of miles of gathering lines and pipelines to carry the gas to consumers remains a major concern (Considine et al. 2010).

1.1.2 Infrastructure and Production Planning

Though the shale gas infrastructure and production planning problem is a relatively new topic, there have been intensive research studies regarding the oil and gas fields infrastructures. Comprehensive studies on deterministic approaches can be dated back to 1998 (Ierapetritou, Floudas, Vasantharajan and Cullick, 1998; Iyer, Grossmann, Vasantharaja and Cullick, 1998; Grothey and McKinnon, 2000; Barnes, Linke and Kokossis, 2002; Kosmidis, Perkins and Pistikopoulos, 2002; Lin and Floudas, 2003; Ortiz-Gomez, Rico-Ramirez and Hernandez-Castro, 2002). Uncertainty has also been considered in some of the literatures.

A dynamic stochastic programming model that incorporates with uncertainty in the size of oil fields is proposed by Haugen (1996). The author only considers the decisions made for scheduling of oil fields. Exploration and production decisions for one field under uncertainty in reserves and oil price are studied by Meister, Clark and Shah (1996). Jonsbraten (1998) uses the progressive hedging algorithm to make decisions for an oil field with uncertainty in oil prices. The problem is formulated as a mixed integer linear programming. The author also studies the sequencing of oil wells under uncertainty in size of oil fields. Both of these two works only include one oil field.

Based on the dependence of the order of revelation of uncertainties on decision maker's action in stochastic programming, the uncertainties can be categorized as exogenous uncertainties and endogenous uncertainties (Jonsbraten 1998). Jonsbraten (1998) investigates decision problems in which actions can affect both the distribution of the uncertainties and the timing of revelation. Besides, there are research studies focusing on problems based on the assumption that uncertain parameters follow a discrete distribution, which could be solved using a finite scenario tree. Goel and Grossmann (2004) propose a model for off-shore gas field development problem with discretely distributed endogenous uncertainties and reformulate it as a mixed binary program.

Problems with continuously distributed random parameters, otherwise, need to be discretized before any of the above techniques can be applied. One alternate solution could be Monte Carlo sampling, but such technique is not considered computationally efficient (Dyer and Stougie 2006, Shapiro and Nemirovski 2005). While discretization may be able to get accurate approximations, it can increase computing cost dramatically when applied to medium or large-sized problems. Vayanos and Kuhn (2011) proposed a methodology for solving dynamic problems with endogenous uncertainties. They suggest approximating the adaptive measurement decisions by piecewise constant functions and the adaptive real-valued decisions by piecewise linear functions of the uncertainties.

As is summarized above, most of the past research works in oil field development planning under uncertainty deal with discretely distributed random parameters or a single oil field. In this study, we seek to propose a model suitable for in-land shale gas infrastructure and production planning. The problem is considered in a broader context as multiple oil fields in a region are presented and the project can last for multiple time horizons. A one-stage model and a multi-stage model with endogenous uncertainties are presented respectively. The assumptions and restrictions of the model are discussed. The approximations which incorporate both linear real-valued decision rules and piecewise constant binary decision rules are presented in detail.

1.2 Urban Freight Transportation Modeling

Urban freight transportation, sometimes also referred to as city logistics, aims to reduce negative externalities, such as emission, noise and congestion, associated with freight activity while supporting their economic and social development (Crainic et al. 2009). Today the problem is even more important and challenging with the growing number of private vehicles, soaring demand of urban freight transportation services and increased recognition of the need for a paradigm shift toward environmentally sustainable logistics and freight technologies.

Urban freight transportation has attracted lots of research efforts in the past decades from different perspectives including transportation regulation, emission estimation and reduction, transportation planning, etc. Most studies about urban freight transportation planning modeled the problem based on a framework of the vehicle routing problem (VRP), with the objective of minimizing the total cost/delay to the carriers or truck companies while satisfying demand consumption constraints. These studies mainly focus on modeling freight activities. However, personal transportation and its impact on the freight transportation planning haven’t been well studied.

1.2.1 Intercity Freight Transportation Assignment and Vehicle Routing Problems

The intercity freight transportation assignment problems that focus on the forecast of transportation flows were intensively studied in 1970s and 1980s. Friesz et al. (1983) provided a survey of the predicative intercity freight network models and discussed the advantage of combined shipper-carrier models and spatial equilibrium models. Friesz et al. (1986) and Harker and Friesz’s (1986a, 1986b) proposed to sequentially and simultaneously model and solve a shipper-carrier static freight assignment problem, respectively. More recently, Agrawal and Ziliaskopoulos (2006) proposed a dynamic shipper-carrier freight assignment model and an iterative approach to solve for the shippers’ equilibrium solution. Nevertheless, due to the need in modeling each shipper and carrier’s sub-network, the shipper-carrier approach is difficult to implemented practice (Crainic et al. 2007). Different from the shipper-career approach, some transshipment network assignment models were proposed to solely address carriers’ transport operations (See Guélat et al. (1990) and Chow and Ritchie (2012) for some examples).

According to Crainic (2000), intercity freight transportation, also known as long-haul transportation, is a tactical (medium-term) planning issue for a transportation agency, while urban freight transportation (city logistics) is more of an operational (short-term) planning issue which is mostly modeled under the framework of a vehicle routing problem (VRP). The common objective of such models are to minimize the total cost/delay to the carriers or truck companies while satisfying demand consumption constraints by designing optimal pick-up or delivery routes from one or several nodes (depots) to a set of other nodes in a transportation network. Vehicle routing problem with time windows (VRPTW) is an extension of VRP which incorporates time constraints for freight pick-up and delivery. Some discussions or surveys of VRP/VRPTW can be found in, e.g. Kulkarni and Bhave (1985), Golden and Assad (1986), Laporte (1992) and Kallehauge et al. (2005). Specifically, in urban freight transportation planning studies, Taniguchi and Thompson (2002) studied a stochastic VRPTW which incorporated travel time variance. Crainic et al. (2009) proposed an integrated model that addresses short-term scheduling of operations and resource management based on a two-tiered distribution structure. Two new problem classes which are extensions of VRPTW were introduced and possible solution avenues were discussed. The two-tiered city logistics model was further extended to address demand uncertainty in Crainic et al. (2011). However, as Ambrosini and Routhier (2004) and Paglione (2006) noted, among the urban freight transportation planning literature, there is a lack of behavioral models that characterize the interactions of private economic and transport agents.

1.2.2 Network Game Models

Nonetheless, the study of competition and cooperation among different road users is not new. Yang et al. (2007) incorporated the routing behaviors of system optimum (SO), user equilibrium (UE) and Cournot-Nash (CN) travelers using a static Stackelberg game with perfect information. In particular, the SO traveler is the leader and the UE and CN travelers are the followers. The UE and CN travelers make their routing decisions in a mixed equilibrium behavior given the SO traveler's routing decision, while the SO traveler optimizes its routes considering the potential reactions of UE and CN travelers towards its routing decision. Since urban freight transportation planning deals with short-term operations and planning issues, a model that can dynamically characterize interactions of road users is necessary.

Dynamic user equilibrium (DUE) captures the routing behaviors of individual travelers in a spatial network in a way that the effective unit delay/cost, including early/late arrival penalties, of traveling on all utilized path at any departure time is identical (see Friesz (2010) for a detailed discussion of DUE). As the first to model timely interactions of freight and personal transportation, this report presents a dynamic Stackelberg game in which the leader is a truck company aiming at optimizing the freight transportation and the followers are individual travelers whose travel behaviors follow DUE with inhomogeneous traffic. The formulation belongs to a challenging set of mathematical programs which is known as dynamic mathematical program with equilibrium constraints (MPEC). Moreover the time shifts in the DUE model make solving this dynamic MPEC even more challenging. Friesz and Mookherjee (2006) proposed to use an implicit fixed point algorithm to accommodate the time shifts and based on this idea. Friesz et al. (2007) discussed two algorithms to solve a dynamic optimal toll problem with equilibrium constraints (DOTPEC) which is a specific type of dynamic MPEC. Yao et al. (2012) introduced toll price uncertainty into the DOTPEC and proposed a bi-level heuristic method to solve the resulting robust DOTPEC. Distinct from the DOTPEC, the lower level of our model is DUE with inhomogeneous traffic which requires a refinement of the traffic dynamics and network loading. Whence, in this study, we propose a new dynamic MPEC model and discuss its theoretical properties. Moreover, to balance the quality of solutions and computational efficiency, instead of using heuristic algorithms we propose a MPCC reformulation and design a projected gradient algorithm to unlock the problem.

1.3 Congestion Derivatives

Congestion pricing is widely accepted as an effective method to reduce congestion, and has the potential to reduce the total social cost (Walters 1961). However, with exception of a few (e.g. Yao et al. 2010 etc.), most congestion pricing schemes and results are derived under two strict, sometimes unrealistic, assumptions: there is no underlying uncertainty and commuters are risk neutral. Hence, whether those dynamic tolls derived from deterministic case are still optimal, or at least suboptimal, in terms of mitigating the total social cost is questionable. More importantly, congestion pricing is not a *market-based mechanism*: a mechanism facilitates a negotiation process between sellers and buyers to determine prices of services according to supply-demand relationship. As the congestion pricing is generally determined by the central planner and may not be changed swiftly without legislative procedure to reflect changes of the supply-demand relationship, it is not characterized as a market-based mechanism by the definition.

Furthermore, optimal congestion pricing requires the central planner to be omnipotent. First, in order to determine the optimal toll, the central planner must have complete and perfect information not only to obtain cost parameters associated with different groups, but also to identify and differentiate each individual from various commuter groups. Second, this central planner must be able to understand the spatial characteristics of the congestion and their impacts on heterogeneous commuters, as well as to master those sophisticated methodologies to calculate and optimize the dynamic toll accordingly. This central planner, often identified as a metropolitan planning organization or the government, generally neither has access to all information nor is able to measure its full impact on individuals or society, not even talking about the level of the sophistication required to calculate and adjust the optimal dynamic toll. Third, even worse, this central planner may not even involve in designing or collecting those tolls. For instance, private section firms, who invest in the bridge, may have rights to collect those tolls. Consequently, given the interest misalignment between private firms and this central planner, the statement that the dynamic toll reduces the total social cost is much vaguer than ever before.

Another important aspect, which we mentioned but not elaborated on, is the heterogeneity nature of commuters. With homogeneous commuters, the central planner does not have the identification problem. However, heterogeneous commuters bring the information asymmetry into the play: the central planner cannot generally identify which group the current commuter belongs to. Without stochasticity and risk preference, this information asymmetry's influence might be marginal. However, as we will see later on, this information asymmetry limits the ability of the central planner or the market-based mechanism to implement different toll schemes based on commuters' characteristics, and also caps the market-based mechanism's ability to achieve the socially optimal solution.

Financial derivatives have been introduced as pure market-based mechanisms. The market of trading financial derivatives can be beneficial to the society by means of aggregating comprehensive market information and pooling the risks of individuals. Hence, the derivatives are widely adopted in a large range of industries: financial industry, agriculture industry, oil industry, electricity industry, etc. Moreover, different from the centralized congestion pricing scheme, the financial derivative market does not require intervention of an omnipotent central planner. Rather, prices of those financial derivatives are determined solely by the supply-demand relationship. Hence, by definition, the financial derivatives are market-based mechanisms. Furthermore, distinct from the central planner's approach, where social characteristics and commuters' information are gathered by the sole effort of the central planner, the market-based mechanism offers a market from which true market information can be derived.

1.3.1 Traffic Bottleneck Model

Vickrey (1969) and Henderson (1974) both are pioneers on simple bottleneck models. However they approach the problem differently. As in Henderson's model, there is no interaction among traffic entering bottleneck at different times which is a perspective that may be restrictive for traffic dynamics (Xin and Levinson 2007). Hence, in this study, we consider Vickrey's model, in which congestion is captured by using a queuing model and delay is calculated as the queuing time behind the bottleneck when demand exceeds capacity. In his paper, Vickrey analyzed a single bottleneck and determined a time-varying toll to eliminate the queue and reduce congestion in a deterministic setting.

Adopting Vickrey's bottleneck model, enormous literature discusses more general equilibria and congestion pricing schemes. With homogeneous commuters, Braid (1989), Arnott et al. (1988), and Arnott et al. (1993) discuss a bottleneck with an elastic demand, where the demand depends on the minimum travel cost. Laih (1994), Bernstein and Sanhouri (1994) and Friesz et al. (2004) discuss alternative toll schemes, such as step tolls and time-varying tolls. Similar to our study, Cohen (1987), Evans (1992), Arnott et al. (1992), and Arnott et al. (1994) extend the single bottleneck problem by considering heterogeneous commuters. Furthermore, Lindsey (2004) proves the existence of bottleneck equilibria in the setting of heterogeneous commuters. Ramadurai et al. (2007) provides a discrete formulation and a solution algorithm to solve the single bottleneck equilibrium problem for general heterogeneous commuters. Van den Berg and Verhoef (2011a, 2011b) analyze the distributional effects and welfare changes for heterogeneous commuters by considering continuously distributed value of time and schedule delay. Furthermore, Arnott et al. (1990) and Yang and Huang (1999) consider a parallel bottlenecks model. In addition, Yang and Huang (2005) provides a more comprehensive literature review on the bottleneck model. Note that when multiple classes or multiple routes are considered, generally, numerical analyses are conducted when closed-form solutions are difficult to derive. Moreover, many works assume deterministic capacity and demand, or a perfectly known elastic demand function. In other words, the stochastic nature of the congestion process is often ignored in the bottleneck literature.

1.3.2 Stochastic Bottleneck Model

Recently, however, more attention and emphasis have been given to stochasticity in bottleneck models. Daniel (1995) analyzes arrival time uncertainty and uses the notion of discrete Markov Chain to model the expected optimal congestion toll. Huang and Lam (2002) extend Daniel's formulation to consider multiple classes of commuters; they employ a route-swapping process as a heuristic solution algorithm. Yin et al. (2004) extend the Huang and Lam (2002) by considering travel time uncertainty. Siu and Lo (2009) model random travel delay in a single bottleneck with a heterogeneous population and arrival probability constraints. Li et al. (2009) consider a uniformly distributed capacity uncertainty for risk-averse commuters in a single bottleneck setting, and give analytical solutions for the equilibrium departure time choice. Arnott et al. (1999) consider demand and capacity uncertainty with constant-elasticity demand and discuss the effect of information asymmetry on the total social cost. Lam (2000) uses the perspective of Henderson (1974) to analyze a congestion uncertainty and consider a network of parallel bottlenecks. Furthermore, a great deal of other papers also address uncertainty in varying settings (e.g. Kraus 1982, D'Ouville and McDonald 1990, Lou et al. 2010, Boyles et al. 2010, and Sumalee and Xu 2011). However, none of those papers allows tolls to be stochastic; likewise, none considers a market-based mechanism.

Friesz et al. (2007) and Yao et al. (2010) are the first two to consider travel cost uncertainty and stochastic tolls as a foundation for introducing congestion derivatives, as market-based mechanisms. In particular, Friesz et al. (2007) use the notion of a European call option, which follows the standard definition as in Black and Scholes (1972), for pricing the delay risks associated with congestion. The option pricing scheme is entirely computational, relying on the notion of dynamic user equilibrium for a general network, and is not readily extended to other types of financial derivatives. While Yao et al. (2010) use the same bottleneck model as ours, the results in Yao et al. (2010) are based on homogeneous commuters, in contrast, this study bases on a more general framework of heterogeneous commuters. Note that the extension to a heterogeneous setting not only is important and nontrivial from the technical aspect, but also brings more insights to our results, which will be elaborated later on. The complexity of analyzing equilibrium and the new insights derived from the heterogeneous setting distinct this study from Yao et al. (2010).

TASK 2 – SHALE GAS INFRASTRUCTURE AND PRODUCTION PLANNING

2.1 Problem Statement

A gas company has several region for gas extraction, and for each region, the gas company has located several gas fields with unknown reserves. As for the case with in-land shale gas production, the production platform is always built next to a gas field that the company decides to exploit. The gas will be processed on-site at each production platform and then transported to a main pipeline. Suppose the main pipeline is built and known and the company is assumed to be aware of the exact locations of the individual gas fields. The company needs to plan the gas production process and build the pipeline to transport the gas to the main pipeline.

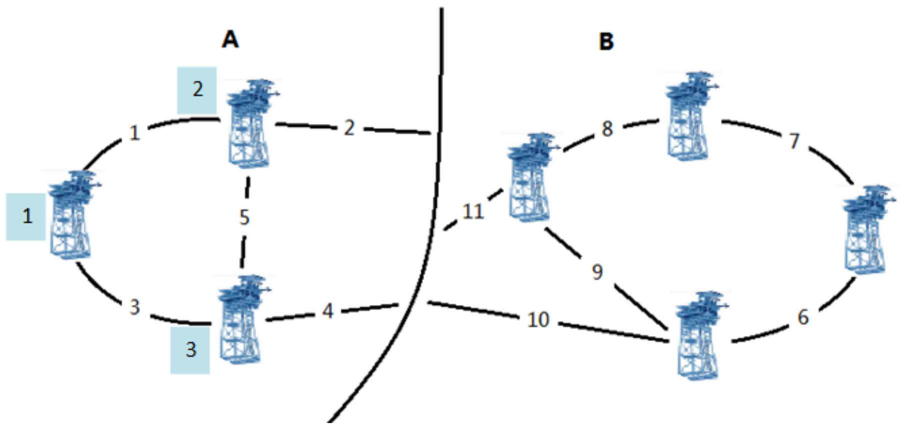


Figure 9. Shale gas network.

The model's formulation requires the notation in Table 27.

Table 27. Notation.

Γ	Time horizon, in years
P	The set of candidate production platforms.
L	The set of possible pipelines between production platforms
o	Main pipeline
$L^{+}(p)$	The set of all ingoing pipeline to production platform p
$L^{-}(p)$	The set of all outgoing pipeline from production platform p
r_p	Maximum production rate at production platform p
d_t	Discount factor at year t
c_g	Unit price for gas
c_c^p	Unit capacity expansion cost for production platform p
c_e^p	Unit gas extraction cost for platform p
c_i^l	Cost for building pipeline l
c_i^p	Cost for building platform p

ξ^p	Gas field size. Random variable.
x_t^p	Binary variable. =1 if production platform p exists in year t
x_t^l	Binary variable. =1 if pipeline l exists in year t
$y_{e,t}^p$	The amount of gas extraction for production platform p in year t
$y_{f,t}^l$	The amount of gas flow through pipeline l in year t
$y_{c,t}^p$	The capacity of production platform p that is increased at the beginning of year t

Assume the company has a project horizon of T years, the time horizon is discretized into T segments, with each one equals to a year. The company makes decisions on platform expansion, gas extraction and platform and pipeline construction at the beginning of each year.

To extract gas from a certain gas reserve, platform has to be installed at the corresponding field. Installed pipelines and platforms are not to be salvaged. Capacity expansion and gas extraction schedules may differ from year to year. All decisions take immediate effect. Once platform is built at p, the size of the gas field ξ^p will be revealed. The total amount of gas extracted should not exceed the reserve of the gas field ξ^p. Once information is revealed, it is assumed not to be forgotten. Annual gas production is also limited by a production rate which may vary field by field, depending on the platform.

The uncertainty is characterized by the reserve of each gas field, which follows a continuous distribution. The company is to make investment and operational decisions each year based on the information it has up to each corresponding year. As random parameters are continuously distributed and decisions are dependent of the uncertainty, a dynamic tree model will not be suitable for the problem. As the uncertainties are unfold over the entire time horizon T based on the investment decisions and operational decisions are dynamic and spread over the entire time horizon, recourse decisions should be considered.

The problem could be stated in detail as below. The company's goal is to maximize the expected net present value of the project. The profit for a single year equals to the sales of gas less the construction cost of pipelines and platforms less the capacity expansion cost at each platform installed less the gas extraction cost. Note that the profit at a later year will be discounted by a factor d_t before added to the objective function.

$$z = \sum_{t \in \Gamma} d_t \mathrm{E} \begin{bmatrix} c_g \sum_{l \in L^+(o)} y_{f,t}^l(\xi) - \sum_{l \in L} c_i^l (x_t^l(\xi) - x_{t-1}^l(\xi)) - \\ \sum_{p \in P} c_i^p (x_t^p(\xi) - x_{t-1}^p(\xi)) - c_c^p y_{c,t}^p(\xi) - c_e^p y_{e,t}^p(\xi) \end{bmatrix}.$$

1. The total amount of gas extracted over the entire time horizon from a single gas field should not exceed the gas field size. Thus,

$$\sum_{t \in \Gamma} y_{e,t}^p(\xi) \le \xi^p \quad \forall p \in P.$$

2. Gas production is limited by a maximum production rate at a particular production platform. Hence,

$$0 \le y^p_{e,t}(\xi) \le r_p \quad \forall p \in P.$$

3. The network subjects to the flow conservation constraint. So,

$$y^p_{e,t}(\xi) + \sum_{l \in L^+(p)} y^l_{f,t}(\xi) \ge \sum_{l \in L^-(p)} y^l_{f,t}(\xi) \quad \forall p \in P.$$

4. Gas flow from a particular production platform should not exceed its capacity. Hence,

$$\sum_{l \in L^-(p)} y^l_{f,t}(\xi) \le \sum_{\tau=1}^{t} y^p_{c,\tau}(\xi) \quad \forall p \in P, t \in \Gamma.$$

5. No gas flow from pipeline l if the pipeline has not been built. Thus,

$$0 \le y^l_{f,t}(\xi) \le M x^l_t(\xi) \quad \forall l \in L, t \in \Gamma.$$

6. No expansion can be constructed if production platform p has not been built. It follows that

$$0 \le y^p_{c,t}(\xi) \le M x^p_t(\xi) \quad \forall p \in P, t \in \Gamma.$$

7. Existing pipelines and production platforms are not to disappear in the network. Thus,

$$x^p_{t-1}(\xi) \le x^p_t(\xi) \quad \forall p \in P, t \in \Gamma,$$
$$x^l_{t-1}(\xi) \le x^l_t(\xi) \quad \forall l \in L, t \in \Gamma.$$

2.2 Infrastructure and Production Planning

2.2.1 One-Stage Infrastructure and Production Planning

In this section, uncertainty is modeled by a probability space $(\mathbb{R}^k, \mathrm{B}(\mathbb{R}^k), \mathrm{P})$ that consists of the sample space $\mathbb{R}^k$ and the Borel σ-algebra $\mathrm{B}(\mathbb{R}^k)$, which is the set of events that are assigned probabilities by the probability measure P. Let $\mathrm{M}_{k,n}$ denote the space of all measureable functions from $\mathbb{R}^k$ to $\mathbb{R}^n$. Let $E(\cdot)$ denote the expectation operator with respect to P and $x \bullet y$ denote the Hadamard product of two vectors $x, y \in \mathbb{R}^n$.

This subsection discusses the one-stage infrastructure and production planning problem with endogenous uncertainty. The decision maker first selects some gas fields, i.e. some elements within ξ to observe. The construction of the platform i, which is the observation of ξ_i will cost the decision maker a price of f_i. Then the decision $y(\xi) \in \mathbb{R}^n$ is selected subject to the field size, flow conservation, platform capacity and network structure, which could be represented as $Ax + By(\xi) \le b(\xi)$, where $B \in \mathbb{R}^{m \times n}$ and at a cost of $c^T y(\xi)$. The decision maker is to find the function $y \in F_{k,n}$ so as to minimize the cost or maximize the profit. Therefore, the decision problem can be formulated in the following general form:

$$\begin{aligned} &\min \ f^T x + \mathrm{E}(c^T y(\xi)) \\ s.t. \quad & x \in \mathbb{R}^k, y \in F_{k,n} \\ & \left. \begin{aligned} & Ax + d + By(\xi) \le h(\xi) \\ & y(\xi) = y(x \bullet \xi) \end{aligned} \right\} \forall \xi \in \Xi , \end{aligned}$$

where $y(\xi) \in \mathbb{R}^n$ denotes the decision/strategy with respect to the stochastic variable. x is a binary decision vector for construction of pipelines and platforms, with x_i forcing the unobserved variable ξ_i equals to 0 and hence has no effect on the strategy function y. Let Ξ denotes a compact polyhedral subset of $\{\xi \in \mathbb{R}^k : \xi_1 = 1\}$, which will enforce that the affine functions of the non-degenerate uncertain parameters could be represented in a compact way as linear functions of $\xi = (\xi_1, ..., \xi_k)$. To approximate the one-stage stochastic problem solution, we use a linear assumption of the underlying data of the form

$$\begin{aligned} y(\xi) = Y\xi \quad Y \in \mathbb{R}^{n \times k}, \\ h(\xi) = H\xi \quad H \in \mathbb{R}^{m \times k}. \end{aligned}$$

This assumption will reduce the admissible decisions/strategies to those that are presented as affine dependence. Then the original stochastic problem is converted to a semi-infinite type as it includes only a finite number of variables but an infinite number of constraints parameterized by $\xi \in \Xi$:

$$\begin{aligned} &\min \ f^T x + \mathrm{E}(c^T Y\xi), \\ s.t. \quad & x \in \mathbb{R}^k, Y \in \mathbb{R}^{n \times k} \\ & \left. \begin{aligned} & Ax + d + BY\xi \le H\xi \\ & y(\xi) = y(x \bullet \xi) \end{aligned} \right\} \forall \xi \in \Xi . \end{aligned}$$

Note that the last constraint in the problem can be restated as

$$|Y_{ij}| \le Mx_j \quad i = 1, ..., n, \ j = 1, ..., k .$$

This set of constraints hold that if ξ_j is not observed, then the decision/strategy $y(\xi) \in \mathbb{R}^n$ should be independent of ξ_j. But M should be large enough to make sure that Y_{ij} is unaffected when $x_j = 1$. The support of the probability measure P could be represented as the form

$$\Xi = \{\xi \in \mathbb{R}^k : W\xi \ge v\} .$$

Proposition 1: For any $\phi \in \mathbb{R}^k$, the following statements are equivalent:

(i) $\phi^T \xi \ge Ax + d$ for all $\xi \in \Xi$, where $\Xi = \{\xi \in \mathbb{R}^k : W\xi \ge v\}$;

(ii) $\exists \lambda \in \mathbb{R}^l$ with $\lambda \ge 0$, $W^T \lambda = z$, and $v^T \lambda \ge Ax + d$.

Proof: Using the duality properties of mixed integer linear programming, we have

$$\begin{aligned} & \phi^T \xi \ge Ax + d \text{ for all } \xi \in \Xi, \text{ where } \Xi = \{\xi \in \mathbb{R}^k : W\xi \ge v\} \\ & \Leftrightarrow \min_{\xi \in \mathbb{R}^k} \left\{ \phi^T \xi : W\xi \ge v \right\} \ge Ax + d \\ & \Leftrightarrow \max_{\lambda \in \mathbb{R}^l} \left\{ v^T \lambda : W^T \lambda = \phi, \lambda \ge 0 \right\} \ge Ax + d \\ & \Leftrightarrow \exists \lambda \in \mathbb{R}^l \text{ with } \lambda \ge 0, \ W^T \lambda = z, \text{ and } v^T \lambda \ge Ax + d. \end{aligned}$$

Then the original problem can be reformulated as

$$\begin{aligned} &\min\ f^T x + c^T Y \mathrm{E}(\xi), \\ s.t.\quad & x \in \mathbb{R}^k, Y \in \mathbb{R}^{n\times k}, \Lambda \in \mathbb{R}^{m\times l}, \\ & \Lambda W + BY = H, \\ & \Lambda v - Ax - d \geq 0, \\ & \Lambda \geq 0. \end{aligned}$$

The above approximation formulation of one-stage stochastic programming can be solved efficiently as a mixed integer binary program. Its size grows polynomially with k, m, n and l, which are the size of the original problem and the number of constraints in the underlying uncertainty set Ξ. The resulting solution is a conservative approximation of the original problem.

2.2.2 Multi-Stage Infrastructure and Production Planning

The dynamic infrastructure and production planning problem in this section is considered in a way that a decision maker makes sequential investment and operational decisions, and obtain observation of the uncertainty parameters $\xi = (\xi_1, ..., \xi_k)$, which are still defined on the probability space $(\mathbb{R}^k, \mathrm{B}(\mathbb{R}^k), \mathrm{P})$, over a finite planning horizon $T := \{1, ..., t\}$. Such problem can be formalized as

$$\begin{aligned} &\min\ \mathrm{E}\Big(\sum_{t\in T} f_t^T x_t(\xi) + c_t^T y_t(\xi)\Big), \\ s.t.\quad & x_t \in F_{k,k}, y_k \in F_{k,n}\ \ \forall t \in T, \\ & \left.\begin{array}{l} \sum_{\tau=1}^{t} A_{t\tau} x_\tau(\xi) + B_{t\tau} y_\tau(\xi) \leq h_t(\xi) \\ x_t(\xi) \in Z_t \\ x_t(\xi) \geq x_{t-1}(\xi) \\ x_t(\xi) = x_t(x_{t-1}(\xi) \bullet \xi) \\ y_t(\xi) = y_t(x_{t-1}(\xi) \bullet \xi) \end{array}\right\} \forall \xi \in \Xi, t \in T, \end{aligned}$$

where $y_t(\xi)$ is a vector that denotes the decision rules/strategies at time t, and $x_t(\xi)$ is an adaptive decision variable that encodes binary information of construction up to time t, which is dependent on the uncertain gas field reserve ξ. The set Z_t, which the adaptive decision variable belongs to is a subset of $\{0,1\}^k$, as it may include constraints which enforce the order of the gas field reserve revealed. For example, a platform can only be built at a certain gas field after another platform is constructed or certain pipelines can be built only after certain stages. If ξ_i is observed and included in the information base at time t, then $x_{t,i}(\xi) = 1$, which will also incur a cost of $f_{t,i}$ and another term $B_{t\tau} y_\tau(\xi)$ in the time t constraint. The constraint $x_t(\xi) \geq x_{t-1}(\xi)$ will enforce that the construction will not be removed, and thus $x_{t,i}(\xi)$ is monotonous, which will stay on 1. The last two constraints in the formulation enforce non-anticipativity, which restrict the decision strategies $y_t(\xi)$ to only depend on gas fields information obtained up to time $t-1$.

The above type of problem involves a multi-stage dynamic programming with adaptive decision rules/strategies and binary recourse variables and is shown to be computationally intractable. To approximate a conservative solution, linear assumptions and partition of uncertainty set are therefore necessary.

Compared to the one-stage production planning model, the multi-stage is more complicated and expensive in computing. Past research on multi-stage stochastic programming has studied the approximation of stochastic programming with continuous recourse variables, of which conservative solutions could be obtained by linear decision rules (Ben-Tal et al. 2004). Also, finite adaptability, which is the middle ground of complete adaptability where the decision-maker has arbitrary adaptability to the exact realization of the uncertainty and static robust formulation where the decision-maker has no information on the realization of the uncertainty, has also proved tractable and efficient when solving multi-stage stochastic programming (Bertsimas. D., and Caramanis, C, 2010). The idea of the approach is partitioning the uncertainty space and receiving information about the realization of the uncertainty, which provides an opportunity to trade off computing expense with optimality. Based on this idea, Vayanos et al. (2011) solve the stochastic programming problem with endogenous uncertainty by approximating the binary decision rules that are piecewise constant and real-valued decisions that are piecewise linear with respect to a pre-selected partition set.

Let Ξ_s denotes the subset of the partition of the uncertainty set

$$\Xi_s := \left\{ \xi \in \Xi : a^i_{s_i - 1} \le \xi_i < a^i_{s_i}, i = 1, ..., k \right\},$$

where $s \in S := \times_{i=1}^{k} \left\{ 1, ..., r_i \right\} \subseteq \square^k$, which separate the original uncertainty set Ξ into $(r_i)^k$ subset by breaking along the ξ_i axis into r_i parts. Thus, the piecewise constant binary decision rule has the form

$$x_t(\xi) = \sum_{s \in S} \mathrm{I}_{\Xi_s}(\xi) x_t^s,$$

where $x_t^s \in \{0,1\}^k, \quad s \in S, \quad t \in T$ and I_{Ξ_s} denotes the indicator function of Ξ_s. Similarly, real-valued decisions can be approximated by piecewise linear decision rules of the form

$$y_t(\xi) = \sum_{s \in S} \mathrm{I}_{\Xi_s}(\xi) Y_t^s \xi,$$

where $Y_t^s \in \square^{n_t \times k}, \quad s \in S, \quad t \in T$. Under the above assumptions, the non-anticipativity constraints

$$x_t(\xi) \ge x_t(x_{t-1}(\xi) \bullet \xi),$$
$$y_t(\xi) \ge y_t(x_{t-1}(\xi) \bullet \xi),$$

can be re-expressed as

$$\forall \xi, \xi', t : x_{t-1}(\xi) \bullet \xi \ge x_{t-1}(\xi') \bullet \xi',$$
$$x_t(\xi) = x_t(\xi'),$$
$$y_t(\xi) = y_t(\xi').$$

Substituting the assumptions into the above equations, we have:

$$\forall s, s', t : x^s_{t-1} \bullet s \ge x^{s'}_{t-1} \bullet s',$$
$$x_t^s = x_t^{s'},$$
$$Y_t^s = Y_t^{s'},$$

$$\forall i, j, s, t \quad \left|Y_{t,ij}^{s}\right| \leq Mx_{t-1,j}^{s}.$$

Note that non-anticipativity across distinct subsets of the partition is enforced in the former part of the constraints while a restriction within each subset is placed in the latter part. Vayanos et al. (2009) then reformulate the above constraints to reduce the notational overhead by suppressing the domain of the variables as follows:

$$\begin{gathered}
\forall j, j', s, s', t : s_{-j} = s'_{-j}, \\
\left|x_{t,j'}^{s} - x_{t,j'}^{s'}\right| \leq x_{t-1,j}^{s}, \\
\left|Y_{t,ij'}^{s} - Y_{t,ij'}^{s'}\right| \leq Mx_{t-1,j}^{s} \quad \forall i, \\
\forall i, j, s, t \quad \left|Y_{t,ij}^{s}\right| \leq Mx_{t-1,j}^{s}.
\end{gathered}$$

Therefore, the original problem is reformulated as

$$\min \mathrm{E}\left(\sum_{t \in T} f_t^T x_t(\xi) + c_t^T y_t(\xi)\right),$$

$$\begin{aligned}
s.t. \quad & x_t \in F_{k,k}, y_k \in F_{k,n} \ \forall t \in T, \\
& \left.\begin{array}{l}
\sum_{\tau=1}^{t} A_{t\tau} x_\tau(\xi) + B_{t\tau} y_\tau(\xi) \leq h_t(\xi) \\
x_t(\xi) \in \mathrm{Z}_t \\
x_t(\xi) \geq x_{t-1}(\xi)
\end{array}\right\} \forall \xi \in \Xi, t \in T, \\
& \left.\begin{array}{l}
\left|x_{t,j'}^{s} - x_{t,j'}^{s'}\right| \leq x_{t-1,j}^{s} \\
\left|Y_{t,ij'}^{s} - Y_{t,ij'}^{s'}\right| \leq Mx_{t-1,j}^{s} \quad \forall i
\end{array}\right\} \forall j, j', s, s', t : s_{-j} = s'_{-j}, \\
& \left|Y_{t,ij}^{s}\right| \leq Mx_{t-1,j}^{s} \quad \forall i, j, s, t.
\end{aligned}$$

where $x_t(\xi) = \sum_{s \in S} \mathrm{I}_{\Xi_s}(\xi) x_t^s$, $y_t(\xi) = \sum_{s \in S} \mathrm{I}_{\Xi_s}(\xi) Y_t^s \xi$. The partition of the uncertainty set could be represented as the form

$\Xi_s = \{\xi \in \mathbb{R}^k : W_s \xi \geq v_s\}$.

We follow similar steps in one-stage stochastic programming. The original problem can be reformulated as a mixed-binary linear programming problem by substituting the piecewise constant and linear assumptions into every other constraints. Hence,

$$\min \sum_{s \in S} p_s \sum_{t \in T} f_t^T x_t^s + c_t^T Y_t^s E(\xi),$$

$$s.t.\quad x_t^s \in Z_t,\, Y_t^s \in \mathbb{R}^{n_t\times k},\, \Lambda_t^s \in \mathbb{R}^{m_t\times l_s}\ \ \forall s,t,$$

$$\left.\begin{array}{l}\Lambda_t^s W_s + \sum_{\tau=1}^{t} B_{t\tau} Y_t^s = H_t^s \\ \Lambda_t^s v_s - \sum_{\tau=1}^{t} A_{t\tau} x_t^s \geq 0 \\ \Lambda_t^s \geq 0 \end{array}\right\} \forall s,t,$$

$$x_t^s \geq x_{t-1}^s \quad \forall s,t,$$

$$\left.\begin{array}{l}\left|x_{t,j'}^s - x_{t,j'}^{s'}\right| \leq x_{t-1,j}^s \\ \left|Y_{t,ij'}^s - Y_{t,ij'}^{s'}\right| \leq M x_{t-1,j}^s \quad \forall i\end{array}\right\} \forall j,j',s,s',t: s_{-j} = s'_{-j},$$

$$\left|Y_{t,ij}^s\right| \leq M x_{t-1,j}^s \quad \forall i,j,s,t.$$

The new formulation of multi-stage stochastic programming has the form of a standard mixed-binary linear programming. Its size is bounded by the size of the original problem, the partition of the uncertainty set and the number of constraints in each underlying uncertainty set Ξ_s. The resulting solution is a conservative approximation of the original problem.

2.3 Numerical Examples

2.3.1 One-Stage Numerical Example

Now considering one-stage decision making in region A of Figure 9, the decision maker is to maximize the profit of gas production. He is to make decisions only once based on the stochastic information. For simplification, constraints on production rate may be omitted. Instead, the size of the gas field will place a limit on the amount of gas extracted. As for region A, three platforms and five pipelines are considered to be built at the very beginning. Once a platform is built, the corresponding field size is revealed. The binary variable will enforce the decision rules not relying on unexploited gas fields. Suppose the input parameters of the problem are summarized in Table 28.

Table 28. Input parameters for one-stage.

ξ^p	Gas field size. Random variable: uniform distributed $U(0,20)$, $U(0,10)$, $U(0,10)$
c_g	Unit price for gas 2
c_c^p	Unit capacity expansion cost for production platform p (0.2, 0.2, 0.2)
c_e^p	Unit gas extraction cost for platform p (0.1, 0.1, 0.1)
c_i^l	Cost for building pipeline l (2, 1, 3, 1, 5)

c_i^p	Cost for building platform p (4, 2, 2)

Following the approximation steps discussed, under the assumption of linear decision strategy and underlying data, we have

$$y(\xi) = Y\xi \quad Y \in \mathbb{R}^{11\times 3},$$

$$h(\xi) = H\xi \quad H \in \mathbb{R}^{9\times 3}.$$

The underlying uncertainty set of stochastic variable ξ can also be represented as

$$\Xi = \{\xi \in \mathbb{R}^3 : W\xi \geq v\}.$$

Together with the constraints that enforce the decision/strategy $y(\xi)$ should be independent of any unobserved ξ_j. Then the original problem is reformulated as the following standard mixed integer problem:

$$\max E\left[c_g (Y_2^f E(\xi) + Y_4^f(\xi)) - \sum_{p=p_1}^{p_3} c_i^p x^p - \sum_{l=l_1}^{l_5} c_i^l x^l - c_c^p Y^c E(\xi) - c_e^p Y^e E(\xi) \right],$$

$$\begin{aligned} s.t.\quad & x^p \in \mathbb{R}^3, x^l \in \mathbb{R}^5, Y \in \mathbb{R}^{11\times 3}, \Lambda \in \mathbb{R}^{9\times 6}, \\ & \Lambda W + BY = H, \\ & \Lambda v \geq 0, \\ & \Lambda \geq 0, \\ & 0 \leq Y_i^f \leq Mx^{l_i} \quad i = 1, 2, \ldots 5, \\ & 0 \leq Y_i^e, Y_i^c \leq Mx^{p_i} \quad i = 1, 2, 3, \\ & 0 \leq Y_i^c \leq Mx^{p_i} \quad i = 1, 2, 3, \\ & 0 \leq Y_{ij}^f, Y_{ij}^e, Y_{ij}^c \leq Mx^{p_j} \quad \forall i,\ j = 1, 2, 3. \end{aligned}$$

where $B = \begin{pmatrix} B_f & B_e & B_c \end{pmatrix}, \quad Y = \begin{bmatrix} Y_f \\ Y_e \\ Y_c \end{bmatrix},$

$$B_f = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 \\ 1 & 0 & 1 & 0 & 0 \\ -1 & 1 & 0 & 0 & 1 \\ 0 & 0 & -1 & 1 & -1 \\ 1 & 0 & 1 & 0 & 0 \\ 0 & 1 & 0 & 0 & 1 \\ 0 & 0 & 0 & 1 & 0 \end{bmatrix}, \quad B_e = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad B_c = \begin{bmatrix} 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix},$$

$$H = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix}, \quad W = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}, \quad v = \begin{bmatrix} 0 \\ 0 \\ 0 \\ -20 \\ -10 \\ -10 \end{bmatrix}.$$

Solving the above problem using GAMS, we obtain the following result,

$$Y_f = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 0 \\ 0 & 0 & 1 \\ 0 & 0 & 0 \end{bmatrix}, \quad Y_c = \begin{bmatrix} 1 & 0 & 0 \\ 1 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix}, \quad Y_e = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$x^p = (1, 1, 1),$$

$$x^l = (1, 1, 0, 1, 0),$$

Objective function $z = 20$.

According to Y_f, we can infer that flow goes through pipeline 1 equals to the size of gas field 1, flow of pipeline 2 equals to the size of gas fields 1 and 2 and pipeline 4 delivers the gas from gas field 3. Besides, pipeline 3 and 5 are not constructed in this problem. From Y_c, we can tell that the capacity of each gas field is enough to deliver the gas to the following pipeline. Also, Y_e indicates that all of the gas within each gas well is exploited to obtain the maximize profit. The results are intuitive. The decision maker is to maximize the profit of the project in one calendar year. Thus, he will need to extract all the gas from each gas field where platforms are built. To transport gas from each platform to the central pipeline, pipelines will be built and platforms will be expanded to a capacity that will pump all the incoming gas to outgoing pipelines. In other words, no gas will be wasted because of insufficient of transportation. From the result, we can infer that pipelines 3 and 5 are not constructed. This is because pipelines 3 and 5 are relatively expensive as compared to other pipelines, and capacity expansion cost is not high enough for the company to build extra pipelines to transport the gas another way. Also, notice that all the gas fields are exploited as $x^p = (1, 1, 1)$.

Under this scenario, the result is the same with a static problem with the size of each gas field fixed and equal to the expectation of each, which also agrees with Monte Carlo sampling. The problem is bounded and solved efficiently, which obviously is an advantage over Monte Carlo sampling.

2.3.2 Multi-Stage Numerical Example

Now, we consider the problem in a more comprehensive way. Assume the company plans taking on the project for a ten-year period, during which time the decision maker needs to organize the gas extraction and transportation process. The goal is to maximize the net present value of the project. Different from the one-stage problem, the decision maker now has multiple years to make decisions for gas production. The size of each gas field is not necessarily revealed in the first period, as the decision maker may choose a later time to reduce the cost of building the platform. However, the revenue of the sales of gas will also decrease when the gas is extracted at a later time. Thus, in the multi-stage shale gas production problem, both strategy and binary variables which represent the construction of platform and pipeline will be dependent of the revelation of the size of gas wells. To make a comparison between multi-stage stochastic programming on the shale gas production project, we assume similar input parameters as for the one-stage problem. Thus, input parameters are shown as in Table 29. Notice that an upper limit is placed on the annual production rate, forcing the decision maker taking account of longer period.

Table 29. Input parameters for multi-stage.

ξ^p	Gas field size. Random variable: uniform distributed $U(0,20)$, $U(0,10)$, $U(0,10)$
r_p	Maximum annual production rate $(2, 2, 2)$
d_t	Discount factor in year t $\frac{1}{1.01^{t-1}}$
c_g	Unit price for gas 2
c_c^p	Unit capacity expansion cost for production platform p $(0.2, 0.2, 0.2)$
c_e^p	Unit gas extraction cost for platform p $(0.1, 0.1, 0.1)$
c_i^l	Cost for building pipeline l $(2, 1, 3, 1, 5)$
c_i^p	Cost for building platform p $(4, 2, 2)$

To approximate the decision rule, we partition the uncertainty set ξ^p into some preselected subsets. Specifically, each ξ^{p_i} $\forall i = 1, 2, 3$ is divided into two parts. With each part denoted by Ξ_s, we have a total of eight subsets with the same probability. The assumption that gas fields follow an uniform distribution makes the partition straightforward and easy to implement. Table 30 shows the partition of the entire uncertainty set.

Table 30. Partition of uncertainty set.

Subset Ξ_s ($P_s = \frac{1}{8}$)	Gas fields ξ^{p_1}, ξ^{p_2}, ξ^{p_3}
$s=1$	$U(0,10)$, $U(0,5)$, $U(0,5)$
$s=2$	$U(10,20)$, $U(0,5)$, $U(0,5)$
$s=3$	$U(0,10)$, $U(5,10)$, $U(0,5)$
$s=4$	$U(10,20)$, $U(5,10)$, $U(0,5)$
$s=5$	$U(0,10)$, $U(0,5)$, $U(5,10)$
$s=6$	$U(10,20)$, $U(0,5)$, $U(5,10)$
$s=7$	$U(0,10)$, $U(5,10)$, $U(5,10)$
$s=8$	$U(10,20)$, $U(5,10)$, $U(5,10)$

Based on the above partition, we approximate the measurement decisions by binary-valued decision rules that are piecewise constant and the real-valued decisions by decision rules that are piecewise constant.

The above optimization problem is a standard mixed-integer programming with its size bounded by the size of the original problem, the partition of the uncertainty set and the number of constraints in each underlying uncertainty set Ξ_s. I use GAMS with CPLEX solver to solve the problem. It takes the software 5 seconds to obtain the result. Some optimal results of decision variables are indicated and explained below. As binary variables in this problem are monotonic, platforms and pipelines will not be deconstructed and only the periods when pipelines and platforms are built are indicated in Table 31.

Table 31. Optimal construction.

	s_1	s_2	s_3	s_4	s_5	s_6	s_7	s_8
l_1	NA	1	1	1	NA	1	1	1
l_2	9	1	1	1	8	1	1	1
l_3	3	NA	NA	NA	6	NA	NA	NA
l_4	1	NA	6	9	6	4	1	1
l_5	NA	NA	NA	NA	NA	NA	NA	NA
p_1	1	1	1	1	1	1	1	1
p_2	1	1	1	1	1	1	1	1
p_3	1	3	1	1	2	3	1	1

The numbers in the table indicate the index of period t. NA means the pipeline/platform is not built under this scenario. Notice that most of the gas fields are exploited during the first period. This is because the revenue of the gas in the first year is more profitable compared to the cost of building pipelines and platforms. We can also see that different results are obtained under different partition subsets. For instance, pipeline 4 is built in a different time period for most scenarios. Platform 3 is not exploited in the first period within subset s_2, s_5 and s_6. Nonetheless, pipeline 5 is never constructed under all scenarios, which agrees with the result of the one-stage gas production model. The difference between each uncertainty subset demonstrates the necessity of partition when approximating the result. The amounts of gas extracted from each platform is indicated in Table 32.

Table 32. Optimal gas extraction.

	p_1	p_2	p_3
t_1	0.929	0.875	0.453
t_2	0.929	0.875	0.375
t_3	1.018	0.875	0.453
t_4	1.018	0.875	0.641
t_5	1.018	0.875	0.641
t_6	1.143	0	0.437
t_7	1.143	0	0.438
t_8	0.964	0.104	0.437
t_9	0.964	0.229	0.375
t_{10}	0.875	0.229	0.375
Total	10.001	4.937	4.625

From the table, we can tell that the total amount of gas extracted from each platform is close to the expectation of each field size. Other factors that might affect the amount of gas extracted include the capacity of the platforms that the gas transports, the construction cost of the pipeline and the layout of the network. Notice that the limitation of gas production rate is not a deciding factor in this case. The amount of capacity expanded during each period is indicated in Table 33.

Table 33. Optimal capacity expansion.

	p_1	p_2	p_3
t_1	0.929	1.804	0.453
t_2	0	0	0
t_3	0.089	0	0.089
t_4	0	0	0.187
t_5	0	0	0
t_6	0.125	0	0.375
t_7	0	0	0

t_8	0	0.104	0
t_9	0	0.125	0.125
t_{10}	0	0	0
Total	1.143	2.033	1.229

It is obvious that decision maker would rather choose a later period to increase capacity as the cost goes down period by period due to the discount factor. Platform 2 has a relatively high capacity, because the gas from platform 1 needs to go through platform 2 to reach the central pipeline. Another reason is that in most cases pipeline 3 is not built due to the high cost which makes pipeline 1 the only way to transport gas from platform 1. The amounts of capacity expanded during each period are indicated in Table 34.

Table 34. Optimal gas flow.

	l_1	l_2	l_3	l_4	l_5
t_1	0.929	1.804	0	0.453	0
t_2	0.929	1.804	0	0.375	0
t_3	0.929	1.804	0.089	0.542	0
t_4	0.929	1.804	0.089	0.73	0
t_5	0.929	1.804	0.089	0.73	0
t_6	0.929	0.929	0.214	0.652	0
t_7	0.929	0.929	0.214	0.652	0
t_8	0.75	0.854	0.214	0.652	0
t_9	0.75	0.979	0.214	0.589	0
t_{10}	0.75	0.979	0.125	0.5	0

Since pipeline 5 is never built under any scenarios, the flow through pipeline 5 will always be zero. However, pipeline 3 is built in t_3 under subset s_1 and in t_6 under subset s_5. Then the flow through pipeline 3 will not be zero as it is calculated as expectation which averages the flow under different scenarios. We also notice that the flow in pipeline 3 goes up in t_6 as pipeline 3 is built under another scenario. This evidence confirms the above explanation.

Finally the objective function is

$$z = 22.817.$$

Compared to the one-stage project, the multi-stage project has a higher net present value which allows the decision maker to earn an extra profit. The conservation approximation obtained lies in-between the situation when the decision-maker has arbitrary adaptability to the exact realization of the uncertainty and the static robust formulation where the decision-maker has no information on the realization of the uncertainty. The approximation could be more accurate if the number of partitions is increased. However, this will also increase the computing cost as the size of the problem is dependent on the partition.

2.4 Conclusions

The shale gas infrastructure and production planning problem is discussed in this study. The problem is modeled as stochastic programming with endogenous uncertainties. Approximations using the adaptive measurement decisions by piecewise constant functions and the adaptive real-valued decisions by piecewise linear functions of the uncertainties could be applied to obtain conservative solution. The decision rule approximation successfully solves the problem with continuously distributed uncertainty parameters. The approximation is considered close to optimal and can be improved by increasing the partition of the uncertainty set. A one-stage numerical is equivalent to a static problem where each field size equals the expectation of the underlying uncertainty parameter. Results of the multi-stage numerical experiment are reasonable. Decision makers are able to obtain more profit by taking on the project for multiple years.

Future work can improve the sophistication of the shale gas infrastructure. A more complicated network with a longer investigating time horizon can be considered to better fit the context of shale gas production. The partition of subset maybe increased if necessary to obtain more accurate solution.

TASK 3 – URBAN FREIGHT TRANSPORTATION PLANNING

3.1 Dynamic Stackelberg Game-Theoretic Modeling

In this study, we consider two types of traffic: freight transportation by trucks and personal transportation by private vehicles. Note that public transportation by buses is ignored in this model since its travel behavior (departure time and route choice) is almost fixed and independent of the behaviors of other vehicles. So in this report, by personal transportation, we refer to private vehicles only. Trucks are controlled by a truck company who aims at minimizing the total transportation cost/delay while satisfying the travel demand (i.e., the total number of trucks required to travel between each origin-destination (O-D) pair to transport freight). Each private vehicle is driven by an individual road user who wants to minimize the personal travel cost/delay in the same time horizon. Thus, the two types of traffic compete for the limited road capacity. Since the individual road users do not cooperate, the impact of each private vehicle's travel behavior on the network traffic is not comparable to that of the truck company. So we model the problem as a Stackelberg game where the truck company is the leader and the other individual road users are the followers. We assume that private vehicles' travel behaviors follow dynamic user equilibrium given those of the trucks. This assumption may not hold for a single-day dynamic traffic assignment problem since it takes time to reach traffic equilibrium. However, we argue that the assumption is acceptable for a truck company that aims at making an optimal everyday transportation schedule in a long time horizon, especially when the travel demands are steady over time.

To understand the interaction of the two types of traffic in the Stackelberg game, we need to address the following questions: 1) How do the trucks' travel behaviors affect the private vehicles? 2) Considering the potential reactions of private vehicles towards its decision, how should the truck company schedule its freight transportation? In the remainder of this section, Section 3.1.1 and 3.1.2 answer the former question and Section 3.1.3 addresses the latter one.

3.1.1 Dynamic User Equilibrium with Inhomogeneous Traffic

We denote the time interval of interest by $\left[t_0, t_f\right] \subset \Re_+^1$. We assume that for all travelers (trucks and private vehicles) there is an identical desired time to arrive at their destinations, T_A. Note that this assumption can be relaxed by allowing different desired arrival time and we can just classify travelers with the same desired arrival time into the same group and model each group explicitly in the DUE which, although complicating the problem formulation, does not change the analysis and structure of the solution approach. To distinguish parameters and variables for trucks from those for private vehicles, we adopt superscript "*tr*" and "*pr*", respectively.

The unit cost to each traveler on a specific path is denoted by the effective unit path delay operator $\Psi_p\left(t, h^{pr}, h^{tr}\right)$, which is defined by the addition of travel cost and penalty cost:

$$\Psi_p\left(t, h^{pr}, h^{tr}\right) = D_p\left(t, h^{pr}, h^{tr}\right) + F\left[t + D_p\left(t, h^{pr}, h^{tr}\right) - T_A\right] \quad \forall p \in \mathrm{P},$$

where $D_p\left(t,h^{pr},h^{tr}\right),\ \forall p\in \mathrm{P}$ denotes the unit delay on path p and P is the set of all paths employed by travelers. t denotes the departure time and h^{pr},h^{tr} denote vectors of flows/departure rates (number of vehicles/trucks entering a path per unit time) of private vehicles and trucks, respectively. A more rigorous definition of h can be found in Friesz (2010) and for simplicity is not stated here. $D_p\left(t,h^{pr},h^{tr}\right)$ is an explicit function of the traveler's departure time but an implicit function of the other travelers' (including trucks' and private vehicles') travel behaviors. The quantification of $D_p\left(t,h^{pr},h^{tr}\right)$ is discussed in detail in Section 3.1.2. $F\left[t+D_p\left(t,h^{pr},h^{tr}\right)-T_A\right]$ denotes early/late arrival penalties and the following equations hold:

$$\begin{cases} \text{if} \quad t+D_p\left(t,h^{pr},h^{tr}\right)>T_A, \quad F\left[t+D_p\left(t,h^{pr},h^{tr}\right)-T_A\right]>0 \\ \text{if} \quad t+D_p\left(t,h^{pr},h^{tr}\right)<T_A, \quad F\left[t+D_p\left(t,h^{pr},h^{tr}\right)-T_A\right]>0 \\ \text{if} \quad t+D_p\left(t,h^{pr},h^{tr}\right)=T_A, \quad F\left[t+D_p\left(t,h^{pr},h^{tr}\right)-T_A\right]=0 \end{cases}.$$

For simplicity, in this study we assume a quadratic penalty function $F\left[x\right]=\alpha x^2$ where α is a constant.

To satisfy the travel demand for all private vehicles, the following flow conservation law must hold:

$$\sum_{p\in \mathrm{P}_{ij}}\int_{t_0}^{t_f} h_p^{pr}\left(t\right)dt=Q_{ij}^{pr} \quad \forall\left(i,j\right)\in W ,$$

where $\left(i,j\right)$ is an O-D pair and W is the set of all O-D pairs. $Q_{ij}^{pr}\in \Re_{++}^1$ is the fixed travel demand on O-D pair $\left(i,j\right)$ for private vehicles and $\mathrm{P}_{ij}\subset \mathrm{P}$ is a set of paths that connect O-D pair $\left(i,j\right)$.

The set of all feasible private vehicle flows can then be defined as

$$\Lambda_0=\left\{h_p^{pr}\ge 0:\sum_{p\in \mathrm{P}_{ij}}\int_{t_0}^{t_f} h_p^{pr}\left(t\right)dt=Q_{ij}^{pr} \quad \forall\left(i,j\right)\in W\right\}\subset\left(L_+^2\left[t_0,t_f\right]\right)^{|\mathrm{P}|}.$$

Theorem 1. A vector of path flows $h^*\in\Lambda_0$ is a DUE if

$$h_p^*\left(t\right)>0,\ p\in \mathrm{P}_{ij}\Rightarrow \Psi_p\left[t,h^*\left(t\right)\ \right]=v_{ij}$$

where $v_{ij}=ess\inf\left[\Psi_p\left(t,h\right):p\in \mathrm{P}_{ij}\right],\quad \forall\left(i,j\right)\in W$.

Proof. See Friesz et al. (1993). □

Let's denote this equilibrium by $DUE\left(\Psi,\Lambda_0,t_0,t_f\right)$.

Theorem 2. $DUE\left(\Psi,\Lambda_0,t_0,t_f\right)$ is equivalent to the following differential variational inequality (DVI):

$$\left.\begin{array}{l}\text{find } h^* \in \Lambda \text{ such that} \\ \sum_{p \in \mathrm{P}_{ij}} \int_{t_0}^{t_f} \Psi_p\left(t, h^*\right)\left(h_p - h_p^*\right) dt \geq 0 \\ \forall h \in \Lambda\end{array}\right\} DVI\left(\Psi, \Lambda, t_0, t_f\right)$$

where $\Lambda = \left\{h \geq 0 : \dfrac{dy_{ij}}{dt} = \sum_{p \in \mathrm{P}_{ij}} h_p(t),\ y_{ij}(t_0) = 0,\ y_{ij}(t_f) = Q_{ij} \quad \forall (i, j) \in W\right\}$ and $y_{ij}(t)$ stands for the volume of traffic that arrived at destination j at time t.

Proof. See Friesz et al. (2011). □

In our model, given path flow of trucks, that of private vehicles will follow DUE. So the associated DVI formulation is

$$\left.\begin{array}{l}\text{find } h^{pr*} \in \Lambda \text{ such that} \\ \sum_{p \in \mathrm{P}_{ij}} \int_{t_0}^{t_f} \Psi_p\left(t, h^{pr*}, h^{tr}\right)\left(h_p^{pr} - h_p^{pr*}\right) dt \geq 0 \\ \forall h^{pr} \in \Lambda\end{array}\right\} DVI^{pr}\left(\Psi, \Lambda, t_0, t_f\right) \tag{1}$$

where $\Lambda = \left\{h^{pr} \geq 0 : \dfrac{dy_{ij}^{pr}}{dt} = \sum_{p \in \mathrm{P}_{ij}} h_p^{pr}(t),\ y_{ij}^{pr}(t_0) = 0,\ y_{ij}^{pr}(t_f) = Q_{ij}^{pr} \quad \forall (i, j) \in W\right\}$ and $y_{ij}^{pr}(t)$ stands for the volume of private vehicles that arrived at destination j at time t.

To solve (1), the evaluation of $\Psi_p\left(t, h^{pr}, h^{tr}\right)$ given h^{pr} and h^{tr} is necessary and it requires the quantification of $D_p\left(t, h^{pr}, h^{tr}\right)$ through dynamic network loading (DNL) which can be based on a link delay model (LDM).

3.1.2 Link Delay Model Based Dynamic Network Loading with Inhomogeneous Traffic

Dynamic network loading (DNL) refers to "the determination of arc-specific volumes, arc-specific exit rates and experienced path delay when departure rates are known for each path" (Friesz et al. 2011). With this process, DUE can be solved efficiently.

Additional notation is necessary. Each path can be represented by a sequence of connected arcs $p = \left\{a_1, a_2, \ldots, a_i, \ldots, a_{m(p)}\right\}$ where $m(p)$ denotes the total number of arcs contained in path p. Flows of trucks and private vehicles that travel along path p exiting arc a_i are denoted by $g_{a_i}^{p,tr}$ and $g_{a_i}^{p,pr}$, respectively. Volume of trucks and private vehicles traveling along path p on arc a_i are denoted by $x_{a_i}^{p,tr}$ and $x_{a_i}^{p,pr}$, respectively.

It is straightforward to derive the following arc dynamics:

$$\left.\begin{aligned}
&\frac{dx_{a_1}^{p,pr}(t)}{dt} = h_p^{pr}(t) - g_{a_1}^{p,pr}(t) \quad \forall p \in \mathrm{P} \\
&\frac{dx_{a_i}^{p,pr}(t)}{dt} = g_{a_{i-1}}^{p,pr}(t) - g_{a_i}^{p,pr}(t) \quad \forall p \in \mathrm{P}, i \in \left[2, m(p)\right] \\
&x_{a_i}^{p,pr}(t_0) = x_{a_i 0}^{p,pr} \quad \forall p \in \mathrm{P}, i \in \left[1, m(p)\right] \\
&\frac{dx_{a_1}^{p,tr}(t)}{dt} = h_p^{tr}(t) - g_{a_1}^{p,tr}(t) \quad \forall p \in \mathrm{P} \\
&\frac{dx_{a_i}^{p,tr}(t)}{dt} = g_{a_{i-1}}^{p,tr}(t) - g_{a_i}^{p,tr}(t) \quad \forall p \in \mathrm{P}, i \in \left[2, m(p)\right] \\
&x_{a_i}^{p,tr}(t_0) = x_{a_i 0}^{p,tr} \quad \forall p \in \mathrm{P}, i \in \left[1, m(p)\right]
\end{aligned}\right\} \qquad (2)$$

where $x_{a_i 0}^{p,pr}$ and $x_{a_i 0}^{p,tr}$ are initial volume of private vehicles and trucks traveling along path p on arc a_i.

Let's define

$$\delta_{a_i p} = \begin{cases} 1, & \text{if arc } a_i \text{ belongs to path p} \\ 0, & \text{otherwise} \end{cases}.$$

The total private vehicle volume on a specific arc a_i at time *t* is

$$x_{a_i}^{pr}(t) = \sum_{p \in \mathrm{P}_{ij}} \delta_{a_i p} x_{a_i}^{p,pr}(t).$$

The total truck volume on a specific arc a_i at time *t* is

$$x_{a_i}^{tr}(t) = \sum_{p \in \mathrm{P}_{ij}} \delta_{a_i p} x_{a_i}^{p,tr}(t).$$

The unit path delay equals the accumulated delays on arcs that compose the path. We denote the delay that a vehicle will experience when it enters arc a_i at time t by $D_{a_i}\left(x_{a_i}(t)\right)$, which is a function of the traffic volume on arc a_i at time *t*. For simplicity, we assume a linear delay function, that is, $D_{a_i}(x) = A_{a_i} + B_{a_i} x$ where A_{a_i} and B_{a_i} are two positive constants. Considering the fact that the size of a truck may be different from that of a private vehicle thus may have a greater impact on congestion than a private vehicle, we assume that

$$x_{a_i}(t) = x_{a_i}^{pr}(t) + \beta x_{a_i}^{tr}(t)$$

where β is a constant and is greater than or equal to 1.

If a vehicle enters path p at time t, we denote its exit time from arc a_i of path p by $\tau_{a_i}^{p}(t)$ and we have

$$\begin{aligned}
&\tau_{a_1}^{p}(t) = t + D_{a_1}\left[x_{a_1}(t)\right] \quad \forall p \in P \\
&\tau_{a_i}^{p}(t) = \tau_{a_{i-1}}^{p}(t) + D_{a_i}\left[x_{a_i}\left(\tau_{a_{i-1}}^{p}(t)\right)\right] \quad \forall p \in P, i \in \left[2, m(p)\right]
\end{aligned}.$$

By applying the chain rule, we can derive the following flow propagation constraints based on the above exit time functions (see Friesz et al. (2001) for more details):

$$\left.\begin{aligned}
&g_{a_1}^{p,pr}\left(t+D_{a_1}\left[x_{a_1}(t)\right]\right)\left(1+D'_{a_1}\left[x_{a_1}(t)\right]\dot{x}_{a_1}\right)=h_p^{pr}(t) \quad \forall p\in\mathrm{P}\\
&g_{a_1}^{p,tr}\left(t+D_{a_1}\left[x_{a_1}(t)\right]\right)\left(1+D'_{a_1}\left[x_{a_1}(t)\right]\dot{x}_{a_1}\right)=h_p^{tr}(t) \quad \forall p\in\mathrm{P}\\
&g_{a_i}^{p,pr}\left(t+D_{a_i}\left[x_{a_i}(t)\right]\right)\left(1+D'_{a_i}\left[x_{a_i}(t)\right]\left(\dot{x}_{a_i}\right)\right)=g_{a_{i-1}}^{p,pr}(t) \quad \forall p\in\mathrm{P}, i\in\left[2,m(p)\right]\\
&g_{a_i}^{p,tr}\left(t+D_{a_i}\left[x_{a_i}(t)\right]\right)\left(1+D'_{a_i}\left[x_{a_i}(t)\right]\left(\dot{x}_{a_i}\right)\right)=g_{a_{i-1}}^{p,tr}(t) \quad \forall p\in\mathrm{P}, i\in\left[2,m(p)\right]
\end{aligned}\right\}$$

where as defined earlier $x_{a_i}(t)=\sum_{p\in\mathrm{P}_{ij}}\delta_{a_i p}\left(x_{a_i}^{p,pr}(t)+\beta x_{a_i}^{p,tr}(t)\right)$. In the above flow propagation constraints, the superscript “′” denotes differentiation with respect to the associated function argument and the overdot “·” refers to differentiation with respect to time.

The time shifts ($t+D_{a_i}[\cdot]$) in the above flow propagation constraints complicate the computation of the solution of DNL. We adopt the approximation proposed by Friesz et al. (2011) to simplify the network loading procedure. By defining $r_{a_i}^p(t)=\dfrac{dg_{a_i}^p(t)}{dt} \quad \forall p\in\mathrm{P}, i\in\left[1,m(p)\right]$, the flow propagation constraints can be approximated by

$$\left.\begin{aligned}
&\frac{dr_{a_1}^{p,pr}(t)}{dt}=R_{a_1}^{p,pr}(x,g,r,h) \quad \forall p\in\mathrm{P}\\
&\frac{dr_{a_i}^{p,pr}(t)}{dt}=R_{a_i}^{p,pr}(x,g,r) \quad \forall p\in\mathrm{P}, i\in\left[2,m(p)\right]\\
&\frac{dr_{a_1}^{p,tr}(t)}{dt}=R_{a_1}^{p,tr}(x,g,r,h) \quad \forall p\in\mathrm{P}\\
&\frac{dr_{a_i}^{p,tr}(t)}{dt}=R_{a_i}^{p,tr}(x,g,r) \quad \forall p\in\mathrm{P}, i\in\left[2,m(p)\right]
\end{aligned}\right\} \qquad (3)$$

where

$$R_{a_1}^{p,pr}(x,g,r,h) = \frac{2h_p^{pr}(t)}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2\left(1+D'_{a_1}\left[x_{a_1}(t)\right]\dot{x}_{a_1}\right)} - \frac{2\left(g_{a_1}^{p,pr}(t)+r_{a_1}^{p,pr}(t)D_{a_1}\left[x_{a_1}(t)\right]\right)}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2}$$

$$\forall p \in \mathrm{P}$$

$$R_{a_i}^{p,pr}(x,g,r) = \frac{2g_{a_{i-1}}^{p,pr}(t)}{\left(D_{a_i}\left[x_{a_i}(t)\right]\right)^2\left(1+D'_{a_i}\left[x_{a_i}(t)\right]\dot{x}_{a_i}\right)} - \frac{2\left(g_{a_i}^{p,pr}(t)+r_{a_i}^{p,pr}(t)D_{a_i}\left[x_{a_i}(t)\right]\right)}{\left(D_{a_i}\left[x_{a_i}(t)\right]\right)^2}$$

$$\forall p \in \mathrm{P}, i \in \left[2, m(p)\right]$$

$$R_{a_1}^{p,tr}(x,g,r,h) = \frac{2h_p^{tr}(t)}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2\left(1+D'_{a_1}\left[x_{a_1}(t)\right]\dot{x}_{a_1}\right)} - \frac{2\left(g_{a_1}^{p,tr}(t)+r_{a_1}^{p,tr}(t)D_{a_1}\left[x_{a_1}(t)\right]\right)}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2}$$

$$\forall p \in \mathrm{P}$$

$$R_{a_i}^{p,tr}(x,g,r) = \frac{2g_{a_{i-1}}^{p,tr}(t)}{\left(D_{a_i}\left[x_{a_i}(t)\right]\right)^2\left(1+D'_{a_i}\left[x_{a_i}(t)\right]\dot{x}_{a_i}\right)} - \frac{2\left(g_{a_i}^{p,tr}(t)+r_{a_i}^{p,tr}(t)D_{a_i}\left[x_{a_i}(t)\right]\right)}{\left(D_{a_i}\left[x_{a_i}(t)\right]\right)^2}$$

$$\forall p \in \mathrm{P}, i \in \left[2, m(p)\right]$$

Theorem 3. If (2) and (3) satisfy the following regularity conditions:

(a). the arc exit time functions $\tau_{a_i}^{p}(t)$ for all *i* are strictly monotonic;

(b). the arc delay functions $D_{a_i}\left(x_{a_i}(t)\right)$ for all *i* are bounded and strictly positive;

(c). $D''_{a_i}\left(x_{a_i}(t)\right)$ exists and is continuous;

(d). $h_p^{tr}(t)$ and $h_p^{pr}(t)$ are continuous.

there exists a unique solution to (2) and (3).

Proof. Per Walter (1988), a unique solution to (2) and (3) exists if the right-hand side of each differential equation in (2) and (3) is continuously differentiable with respect to $x_{a_i}^{pr}$, $x_{a_i}^{tr}$, $g_{a_i}^{p,pr}$, $g_{a_i}^{p,tr}$, $r_{a_i}^{p,pr}$ and $r_{a_i}^{p,tr}$. It is obvious that the differential equations in (2) have this property. The remaining effort is on proving that those in (3) have the same property, that is, $R_{a_i}^{p,pr}$, $R_{a_i}^{p,tr}$ are differentiable with respect to $x_{a_i}^{pr}$, $x_{a_i}^{tr}$, $g_{a_i}^{p,pr}$, $g_{a_i}^{p,tr}$, $r_{a_i}^{p,pr}$ and $r_{a_i}^{p,tr}$. For simplicity, here we just show the closed-form expressions for those derivatives of $R_{a_1}^{p,pr}$ and $R_{a_1}^{p,tr}$, similar results can be established for $R_{a_i}^{p,pr}$ and $R_{a_i}^{p,tr}$ for $i \in \left[2, m(p)\right]$.

It is not difficult to derive the following closed-form expressions for derivatives of $R_{a_i}^{p,pr}$ and $R_{a_i}^{p,tr}$:

$$\frac{\partial R_{a_1}^{p,pr}}{\partial x_{a_1}^{pr}} = \frac{\partial R_{a_1}^{p,pr}}{\partial x_{a_1}^{tr}} = X_{a_1}^{pr} - \frac{2r_{a_1}^{p,pr}(t) D'_{a_1}\left[x_{a_1}(t)\right]}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2} + \frac{4\left(g_{a_1}^{p,pr}(t) + r_{a_1}^{p,pr}(t) D_{a_1}\left[x_{a_1}(t)\right]\right) D_{a_1}\left[x_{a_1}(t)\right] D'_{a_1}\left[x_{a_1}(t)\right]}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^4}$$

$$\forall p \in \mathrm{P}$$

$$\frac{\partial R_{a_1}^{p,tr}}{\partial x_{a_1}^{pr}} = \frac{\partial R_{a_1}^{p,tr}}{\partial x_{a_1}^{tr}} = X_{a_1}^{tr} - \frac{2r_{a_1}^{p,tr}(t) D'_{a_1}\left[x_{a_1}(t)\right]}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2} + \frac{4\left(g_{a_1}^{p,tr}(t) + r_{a_1}^{p,tr}(t) D_{a_1}\left[x_{a_1}(t)\right]\right) D_{a_1}\left[x_{a_1}(t)\right] D'_{a_1}\left[x_{a_1}(t)\right]}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^4}$$

$$\forall p \in \mathrm{P}$$

$$\frac{\partial R_{a_1}^{p,pr}}{\partial g_{a_1}^{p,pr}} = \frac{2h_p^{pr}(t)}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2} \frac{D'_{a_1}\left[x_{a_1}(t)\right]}{\left(1 + D'_{a_1}\left[x_{a_1}(t)\right]\left(h_p^{pr}(t) - g_{a_1}^{p,pr}(t)\right)\right)^2} - \frac{2g_{a_1}^{p,pr}(t)}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2} \quad \forall p \in \mathrm{P}$$

$$\frac{\partial R_{a_1}^{p,tr}}{\partial g_{a_1}^{p,tr}} = \frac{2h_p^{tr}(t)}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2} \frac{D'_{a_1}\left[x_{a_1}(t)\right]}{\left(1 + D'_{a_1}\left[x_{a_1}(t)\right]\left(h_p^{tr}(t) - g_{a_1}^{p,tr}(t)\right)\right)^2} - \frac{2g_{a_1}^{p,tr}(t)}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2} \quad \forall p \in \mathrm{P}$$

$$\frac{\partial R_{a_1}^{p,pr}}{\partial r_{a_1}^{p,pr}} = \frac{\partial R_{a_1}^{p,tr}}{\partial r_{a_1}^{p,tr}} - \frac{2}{D_{a_1}\left[x_{a_1}(t)\right]} \quad \forall p \in \mathrm{P}$$

where

$$X_{a_1}^{pr} = \frac{-2h_p^{pr}(t)\left(Y_{a_1}^{pr} + Z_{a_1}^{pr}\right)}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^4 \left(1 + D'_{a_1}\left[x_{a_1}(t)\right]\left(h_p^{pr}(t) - g_{a_1}^{p,pr}(t)\right)\right)^2} \quad \forall p \in \mathrm{P}$$

$$X_{a_1}^{tr} = \frac{-2h_p^{tr}(t)\left(Y_{a_1}^{tr} + Z_{a_1}^{tr}\right)}{\left(D_{a_1}\left[x_{a_1}(t)\right]\right)^4 \left(1 + D'_{a_1}\left[x_{a_1}(t)\right]\left(ht_p^{pr}(t) - g_{a_1}^{p,tr}(t)\right)\right)^2} \quad \forall p \in \mathrm{P}$$

$$Y_{a_1}^{pr} = 2D_{a_1}\left[x_{a_1}(t)\right] D'_{a_1}\left[x_{a_1}(t)\right]\left(1 + D'_{a_1}\left[x_{a_1}(t)\right]\left(h_p^{pr}(t) - g_{a_1}^{p,pr}(t)\right)\right) \quad \forall p \in \mathrm{P}$$

$$Y_{a_1}^{tr} = 2D_{a_1}\left[x_{a_1}(t)\right] D'_{a_1}\left[x_{a_1}(t)\right]\left(1 + D'_{a_1}\left[x_{a_1}(t)\right]\left(h_p^{tr}(t) - g_{a_1}^{p,tr}(t)\right)\right) \quad \forall p \in \mathrm{P}$$

$$Z_{a_1}^{pr} = \left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2 \left(D''_{a_1}\left[x_{a_1}(t)\right]\left(h_p^{pr}(t) - g_{a_1}^{p,pr}(t)\right)\right) \quad \forall p \in \mathrm{P}$$

$$Z_{a_1}^{tr} = \left(D_{a_1}\left[x_{a_1}(t)\right]\right)^2 \left(D''_{a_1}\left[x_{a_1}(t)\right]\left(h_p^{tr}(t) - g_{a_1}^{p,tr}(t)\right)\right) \quad \forall p \in \mathrm{P}$$

Thus the theorem is proven. □

So given h^{pr} and h^{tr} as constants, solving (2) and (3), also known as the differential algebraic equation (DAE) system, we can evaluate $x_{a_i}(t)$, $D_{a_i}\left[x_{a_i}(t)\right]$ and $\tau_{a_i}^p(t)$ for all $p \in \mathrm{P}, i \in \left[2, m(p)\right]$, and then quantify unit path delay using the following function

$$D_p(t) = \sum_{i=1}^{m(p)} \left[\tau_{a_i}^p(t) - \tau_{a_{i-1}}^p(t)\right] = \tau_{a_{m(p)}}^p(t) - t .$$

It was first proven by Friesz et al. (1993) that a closed-form formulation of DUE can preserve first-in-first-out (FIFO) rule under mild assumptions. In the remaining of this section, we prove a similar result for DUE with inhomogeneous traffic.

First we need to introduce the following lemma.

Lemma 1. If function $f:\Re \to \Re$ is invertible and differentiable with a derivative f':

$$\left[f^{-1}\right]'(z) = 1 \big/ f'\left[f^{-1}(z)\right]$$

Proof. See Friesz et al. (1993).

Now we can demonstrate the following theorem.

Theorem 4. For an arc delay function $D_{a_i}\left(x_{a_i}(t)\right) = A_{a_i} + B_{a_i}\left(x_{a_i}^{pr}(t) + \beta x_{a_i}^{tr}(t)\right)$, the resulting arc exit time function τ_{a_i} is strictly increasing thus invertible. Consequently, the FIFO rule is satisfied.

Proof. We partition the time into appropriate intervals and assume without loss of generality that $x_{a_i}^{pr}(0) = x_{a_i}^{tr}(0) = 0$. We in addition assume that the first vehicle enters arc a_i at time 0 and it does not matter whether it is a private vehicle or a truck. We denote the time that the first vehicle exits arc a_i by t_1 and we have by definition

$$t_1 = D_{a_i}(0) = A_{a_i}$$

and

$$x_{a_i}(t) = x_{a_i}^{pr}(t) + \beta x_{a_i}^{tr}(t) = \int_0^t u_{a_i}^{pr}(s)ds + \beta \int_0^t u_{a_i}^{tr}(s)ds, \quad \forall t \in [0, t_1]$$

where $u_{a_i}^{pr}(t) = \sum_{p \in P} h_p^{pr}(t)\delta_{a_i p}$ and $u_{a_i}^{tr}(t) = \sum_{p \in P} h_p^{tr}(t)\delta_{a_i p}$ denote the flow of private vehicles and trucks entering arc a_i , respectively.

Hence for any $t \in [0, t_1]$, we denote the exit time function by $\tau_{1,a_i}(t)$, and we have

$$\tau_{1,a_i}(t) = t + D_{a_i}(t) = t + A_{a_i} + B_{a_i}\left[\int_0^t u_{a_i}^{pr}(s)ds + \beta \int_0^t u_{a_i}^{tr}(s)ds\right].$$

Note that $t_1 = \tau_{1,a_i}(0)$ and $\tau_{1,a_i}(t)$ is differentiable with

$$\tau'_{1,a_i}(t) = 1 + B_{a_i}\left[u_{a_i}^{pr}(t) + \beta u_{a_i}^{tr}(t)\right] \tag{i}$$

which is strictly positive since B_{a_i} is positive and $u_{a_i}^{pr}(t)$ and $u_{a_i}^{tr}(t)$ are nonnegative. Hence, $\tau_{1,a_i}(t)$ is increasing on $[0, t_1]$ and a well defined inverse function $\tau_{1,a_i}^{-1}(t)$ exists on $\left[\tau_{a_1}(0), \tau_{a_1}(t_1)\right]$.

Let $t_2 = \tau_{a_1}(t_1)$, $\left[\tau_{a_1}(0), \tau_{a_1}(t_1)\right] \equiv [t_1, t_2]$.

Note that the commuters traveling on arc a_i at time $t \in [t_1, t_2]$ are those who entered the arc during the interval $\left[\tau_{1,a_i}^{-1}(t), t\right]$. Hence, if we denote the exit time for commuters entering arc a_i during the interval $[t_1, t_2]$ by $\tau_{2,a_i}(t)$, then for all $t \in [t_1, t_2]$,

$$\tau_{2,a_i}(t) = t + A_{a_i} + B_{a_i}\left[\int_{\tau_{1,a_i}^{-1}(t)}^t u_{a_i}^{pr}(s)ds + \beta \int_{\tau_{1,a_i}^{-1}(t)}^t u_{a_i}^{tr}(s)ds\right]$$

and $\tau_{2,a_i}(t_1) = \tau_{1,a_i}(t_1) = t_2$.

The derivative of $\tau_{2,a_i}(t)$ is given by

$$\begin{aligned}
\tau'_{2,a_i}(t) &= 1 + B_{a_i}\left[u_{a_i}^{pr}(t) - u_{a_i}^{pr}\left[\tau_{1,a_i}^{-1}(t)\right]\left[\tau_{1,a_i}^{-1}\right]'(t) + \beta u_{a_i}^{tr}(t) - \beta u_{a_i}^{tr}\left[\tau_{1,a_i}^{-1}(t)\right]\left[\tau_{1,a_i}^{-1}\right]'(t)\right] \\
&= 1 + B_{a_i}u_{a_i}^{pr}(t) - \frac{B_{a_i}u_{a_i}^{pr}\left[\tau_{1,a_i}^{-1}(t)\right]}{\tau'_{1,a_i}\left[\tau_{1,a_i}^{-1}(t)\right]} + B_{a_i}\beta u_{a_i}^{tr}(t) - \frac{B_{a_i}\beta u_{a_i}^{tr}\left[\tau_{1,a_i}^{-1}(t)\right]}{\tau'_{1,a_i}\left[\tau_{1,a_i}^{-1}(t)\right]} \\
&= 1 + B_{a_i}u_{a_i}^{pr}(t) - \frac{B_{a_i}u_{a_i}^{pr}\left[\tau_{1,a_i}^{-1}(t)\right]}{1 + B_{a_i}\left(u_{a_i}^{pr}\left[\tau_{1,a_i}^{-1}(t)\right] + \beta u_{a_i}^{tr}\left[\tau_{1,a_i}^{-1}(t)\right]\right)} + B_{a_i}\beta u_{a_i}^{tr}(t) - \frac{B_{a_i}\beta u_{a_i}^{tr}\left[\tau_{1,a_i}^{-1}(t)\right]}{1 + B_{a_i}\left(u_{a_i}^{pr}\left[\tau_{1,a_i}^{-1}(t)\right] + \beta u_{a_i}^{tr}\left[\tau_{1,a_i}^{-1}(t)\right]\right)} \\
&= B_{a_i}\left(u_{a_i}^{pr}(t) + \beta u_{a_i}^{tr}(t)\right) - \frac{1}{1 + B_{a_i}\left(u_{a_i}^{pr}\left[\tau_{1,a_i}^{-1}(t)\right] + \beta u_{a_i}^{tr}\left[\tau_{1,a_i}^{-1}(t)\right]\right)} \\
&> B_{a_i}\left(u_{a_i}^{pr}(t) + \beta u_{a_i}^{tr}(t)\right) \geq 0
\end{aligned}$$

The second and third equalities are derived using Lemma 1 and equation (i), respectively.

Thus, we can again conclude that $\tau_{2,a_i}(t)$ is increasing on $[t_1, t_2]$ and a well defined inverse function $\tau_{2,a_i}^{-1}(t)$ exists on $\left[\tau_{a_1}(t_1), \tau_{a_1}(t_2)\right]$.

We proceed by induction. For *n = 2*, we have already shown that

$$\tau_{2,a_i}(t) = t + A_{a_i} + B_{a_i}\left[\int_{\tau_{1,a_i}^{-1}(t)}^{t} u_{a_i}^{pr}(s)ds + \beta\int_{\tau_{1,a_i}^{-1}(t)}^{t} u_{a_i}^{tr}(s)ds\right]$$
$$\tau_{2,a_i}(t_1) = \tau_{1,a_i}(t_1) = t_2$$
$$\tau'_{2,a_i}(t) > B_{a_i}\left(u_{a_i}^{pr}(t) + \beta u_{a_i}^{tr}(t)\right) \geq 0$$

Then we choose any $k > 2$. Suppose that for $n = k$, the exit time function $\tau_{k,a_i}(t)$ is invertible and the following conditions hold:

$$\tau_{k,a_i}(t) = t + A_{a_i} + B_{a_i}\left[\int_{\tau_{k-1,a_i}^{-1}(t)}^{t} u_{a_i}^{pr}(s)ds + \beta\int_{\tau_{k-1,a_i}^{-1}(t)}^{t} u_{a_i}^{tr}(s)ds\right] \quad \text{(ii)}$$
$$\tau_{k,a_i}(t_{k-1}) = \tau_{k-1,a_i}(t_{k-1}) = t_k \quad \text{(iii)}$$
$$\tau'_{k,a_i}(t) > B_{a_i}\left(u_{a_i}^{pr}(t) + \beta u_{a_i}^{tr}(t)\right) \text{ for all } t \in [t_{k-1}, t_k] \quad \text{(iv)}$$

We wish to show that for *n = k + 1*, if denote $t_{k+1} = \tau_{k,a_i}(t_k)$, then the exit time function $\tau_{k+1,a_i}(t_k)$ satisfies the following conditions:

$$\tau_{k+1,a_i}(t) = t + A_{a_i} + B_{a_i}\left[\int_{\tau_{k,a_i}^{-1}(t)}^{t} u_{a_i}^{pr}(s)ds + \beta\int_{\tau_{k,a_i}^{-1}(t)}^{t} u_{a_i}^{tr}(s)ds\right] \quad \text{(v)}$$
$$\tau_{k+1,a_i}(t_k) = \tau_{k,a_i}(t_k) = t_{k+1} \quad \text{(vi)}$$
$$\tau'_{k+1,a_i}(t) > B_{a_i}\left(u_{a_i}^{pr}(t) + \beta u_{a_i}^{tr}(t)\right) \text{ for all } t \in [t_k, t_{k+1}] \quad \text{(vii)}$$

By definition, it is not difficult to show that equation (v) is satisfied. So we only need to derive equations (vi) and (viii) in the rest of this proof.

First, similar to the derivation of $\tau'_{2,a_i}(t)$ we can show equation (vii) by the following:

$$\tau'_{k+1,a_i}(t) = 1 + B_{a_i}\left[u_{a_i}^{pr}(t) - u_{a_i}^{pr}\left[\tau_{k,a_i}^{-1}(t)\right]\left[\tau_{k,a_i}^{-1}\right]'(t) + \beta u_{a_i}^{tr}(t) - \beta u_{a_i}^{tr}\left[\tau_{k,a_i}^{-1}(t)\right]\left[\tau_{k,a_i}^{-1}\right]'(t)\right]$$

$$= 1 + B_{a_i}u_{a_i}^{pr}(t) - \frac{B_{a_i}u_{a_i}^{pr}\left[\tau_{k,a_i}^{-1}(t)\right]}{\tau'_{k,a_i}\left[\tau_{k,a_i}^{-1}(t)\right]} + B_{a_i}\beta u_{a_i}^{tr}(t) - \frac{B_{a_i}\beta u_{a_i}^{tr}\left[\tau_{k,a_i}^{-1}(t)\right]}{\tau'_{k,a_i}\left[\tau_{k,a_i}^{-1}(t)\right]}$$

$$= B_{a_i}\left(u_{a_i}^{pr}(t) + \beta u_{a_i}^{tr}(t)\right) - \frac{1}{1 + B_{a_i}\left(u_{a_i}^{pr}\left[\tau_{k,a_i}^{-1}(t)\right] + \beta u_{a_i}^{tr}\left[\tau_{k,a_i}^{-1}(t)\right]\right)}$$

$$> B_{a_i}\left(u_{a_i}^{pr}(t) + \beta u_{a_i}^{tr}(t)\right) \geq 0$$

Then by equation (iii) and the assumed invertibility of $\tau_{k,a_i}(t)$ and $\tau_{k-1,a_i}(t)$, we have

$$t_{k-1} = \tau_{k,a_i}^{-1}(t_k) \text{ and } t_{k-1} = \tau_{k-1,a_i}^{-1}(t_{k-1}).$$

This together with equation (v) yields

$$\tau_{k+1,a_i}(t_k) = t_k + A_{a_i} + B_{a_i}\left[\int_{\tau_{k,a_i}^{-1}(t_k)}^{t_k} u_{a_i}^{pr}(s)ds + \beta\int_{\tau_{k,a_i}^{-1}(t_k)}^{t_k} u_{a_i}^{tr}(s)ds\right]$$

$$= t_k + A_{a_i} + B_{a_i}\left[\int_{t_{k-1}}^{t_k} u_{a_i}^{pr}(s)ds + \beta\int_{t_{k-1}}^{t_k} u_{a_i}^{tr}(s)ds\right]$$

$$= t_k + A_{a_i} + B_{a_i}\left[\int_{\tau_{k-1,a_i}^{-1}(t_{k-1})}^{t_k} u_{a_i}^{pr}(s)ds + \beta\int_{\tau_{k-1,a_i}^{-1}(t_{k-1})}^{t_k} u_{a_i}^{tr}(s)ds\right]$$

$$= \tau_{k,a_i}(t_k)$$

and thus equation (vi) holds.

Consequently, the exit time function $\tau_{a_i}(t)$ is everywhere continuous and increasing on $\Re_+$ which indicates that $\tau_{a_i}(t_1) > \tau_{a_i}(t_2)$ if $t_1 > t_2$. Thus the FIFO rule holds. □

3.1.3 Formulation of the Stackelberg Game

In the proposed Stackelberg game, the leader (the truck company) aims at minimizing its total cost while satisfying the travel demand over the time frame of interest, which can be represented by (4) and (5), respectively:

$$\min \sum_{p\in \mathrm{P}_{ij}} \int_{t_0}^{t_f} \Psi_p\left(t, h^{pr*}, h^{tr}\right) h_p^{tr} dt \tag{4}$$

$$\sum_{p\in \mathrm{P}_{ij}} \int_{t_0}^{t_f} h_p^{tr}(t)dt = Q_{ij}^{tr},\ h_p^{tr} \geq 0 \quad \forall (i,j) \in W \tag{5}$$

where

$$\Psi_p\left(t, h^{pr}, h^{tr}\right) = D_p\left(t, h^{pr}, h^{tr}\right) + F\left[t + D_p\left(t, h^{pr}, h^{tr}\right) - T_A\right] \quad \forall p \in \mathrm{P}.$$

Then the problem can be represented by {(1), (2), (3), (4), (5)} which is a dynamic mathematical program with equilibrium constraints (MPEC).

In (4), h^{pr*} stands for the vector of equilibrium flows of private vehicles and h^{tr} is the vector of truck flows. Equation (4) minimizes the total effective delay experienced by all the trucks that travel on the network in time interval $\left[t_0, t_f\right]$. Equation (5) is the demand consumption constraint for trucks. (4) and (5) compose the upper level of the dynamic MPEC. (1), (2) and (3) which characterize the equilibrium flows of private vehicles compose the lower level of the dynamic MPEC.

Existence of solutions to this dynamic MPEC is a crucial issue. It is resolved if we can show that for any set of truck flows $h_p^{tr}(t),\ \forall p$ that are feasible to (5), (1) has a solution, that is, h^{pr*}. If $\Psi_p\left(t,h^{pr},h^{tr}\right)$ for all p is continuous and the feasible set Λ in (1) is compact, the fixed point theory of multi-valued mappings in topological vector spaces discussed by Browder (1968) can be applied to show that there exists a solution to (1). So, existence results are general if the DUE is based on the formulation (1). However, a rigorous proof of existence when regularity conditions are imposed entirely on the path delay operators without the assumption that the path flows are a priori bounded from above is still challenging and remains to be addressed by future studies.

3.2 Algorithm Design

Although a rigorous proof is not available, we still have a general property of existence of solutions and we can develop or apply an algorithm to find the solution. Since the dynamic MPEC is nonconvex and the DNL process in solving the lower level DUE requires complex nested calculations, we reformulate the problem as a mathematical program with complementarity constraints (MPCC), which is a single-level problem computable by standard optimization techniques. In particular, the DUE is formulated as the following complementarity problem:

$$\begin{aligned}
&\left(\Psi_p\left(t,h_p^{pr},h_p^{tr}\right)-\mu_{ij}\right)\perp h_p^{pr} \quad \forall p\in ij\\
&\Psi_p\left(t,h_p^{pr},h_p^{tr}\right)-\mu_{ij}\geq 0 \qquad \forall p\in ij\\
&h^{pr}\geq 0
\end{aligned} \tag{6}$$

where $h^{pr}\in\Lambda$, and $\mu := \left(\mu_{ij} : ij\in W\right)$. With complementarity constraints (6) substituted for DUE (1), the MPCC reformulation of the proposed urban freight model can be represented by {(2), (3), (4), (5), (6)}.

Since the complementarity constraints might not satisfy certain constraint qualifications that are necessary to guarantee convergence of the solution (Rodrigues and Monteiro, 2006), to solve the MPCC, we penalize the complementarity constraints and obtain the augmented objective function as:

$$\begin{aligned}
&U\left(h^{pr},h^{tr},\mu,M\right)\\
&:=\sum_{p\in P_{ij}}\int_{t_0}^{t_f}\Psi_p\left(t,h^{pr},h^{tr}\right)h_p^{tr}\,dt\\
&\quad+M\sum_{p\in P_{ij}}\int_{t_0}^{t_f}\left[\left(\Psi_p\left(t,h_p^{pr},h_p^{tr}\right)-\mu_w\right)h_p^{pr}\right]^2 dt\\
&\quad+M\sum_{p\in P_{ij}}\int_{t_0}^{t_f}\left[\max\left\{\mu_{ij}-\Psi_p\left(t,h_p^{pr},h_p^{tr}\right),0\right\}\right]^2 dt
\end{aligned} \tag{7}$$

where M is a large number.

By substituting (7) for (4), we have finalized the urban freight transportation planning problem as a single-level nonlinear program {(2), (3), (5), (6), (7)}. We design the following projected gradient algorithm to solve this nonlinear program.

Projected gradient algorithm:

Step 0. Initialization. Identify an initial feasible solution $u^k := \left(h^{pr,k}, h^{tr,k}, \mu_{ij}^k\right)^T$ and set k = 0;

Step 1. Solve the optimal control subproblem:

$$
\begin{aligned}
&\min_{v} \int_{t_0}^{t_f} \frac{1}{2}\left\| h^{pr,k}(t) - \alpha F_1\left(t, h^{pr,k}(t), h^{tr,k}(t), \mu^k\right) - h^{pr}(t)\right\|_2^2 dt \\
&+\int_{t_0}^{t_f} \frac{1}{2}\left\| h^{tr,k}(t) - \alpha F_2\left(t, h^{pr,k}(t), h^{tr,k}(t), \mu^k\right) - h^{tr}(t)\right\|_2^2 dt \\
&+\int_{t_0}^{t_f} \frac{1}{2}\left\| \mu^k - \alpha F_3\left(t, h^{pr,k}(t), h^{tr,k}(t), \mu^k\right) - \mu \ \right\|_2^2 dt \\
&s.t. \\
&\frac{dy_{ij}^{pr}(t)}{dt} = \sum_{p \in P_{ij}} h_p^{pr}(t) \\
&\frac{dy_{ij}^{tr}(t)}{dt} = \sum_{p \in P_{ij}} h_p^{tr}(t) \\
&y_{ij}^{pr}(t_0) = 0, y_{ij}^{pr}(t_f) = Q_{ij}^{pr} \\
&y_{ij}^{tr}(t_0) = 0, y_{ij}^{tr}(t_f) = Q_{ij}^{tr}
\end{aligned}
$$

Denote the solution by $u^{k+1} := \left(h^{pr,k+1}, h^{tr,k+1}, \mu^{k+1}\right)^T$.

Step 2. Stop if $\left\|u^{k+1} - u^k\right\| \le \varepsilon_1$, where $\varepsilon_1 \in \Re_{++}^1$ is a preset scalar. Otherwise, set M = CM, go to Step 1.

In the pseudo-code, $F_1 := \partial U / \partial h^{pr}$, $F_2 := \partial U / \partial h^{tr}$, $F_3 := \partial U / \partial \mu$ and C are constants that are great than 1. Note that since the problem is nonconvex in general, by the proposed solution approach, only local optimal solutions can be guaranteed.

3.3 Numerical Test

The algorithm is tested on Nguyen-Dupuis network which consists of 19 nodes and 25 links as shown by Figure 10. We set $t_0 = 100, t_f = 175$ and define a desired arrival time $T_A = 160$ for the trucks as well as private vehicles. This planning horizon is then discretized into 300 time intervals and each of which is 0.25 time units long. Each time unit represents 1 minute in the real world.

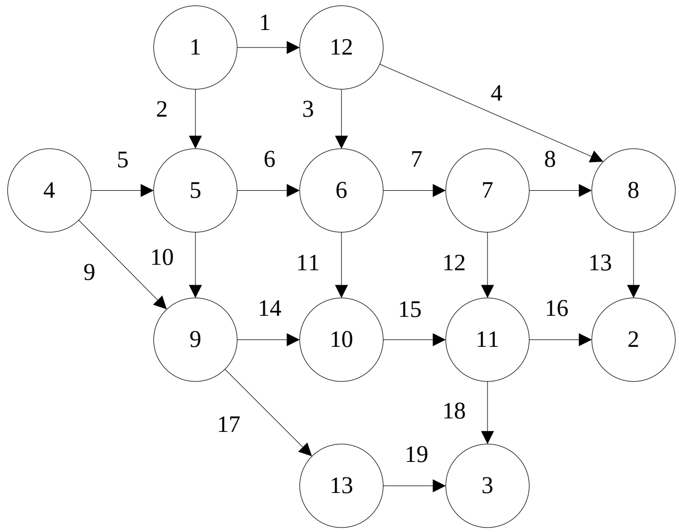


Figure 10. Nguyen-Dupuis network

Specifically, we focus on the set of O-D pairs $W=\{(1,2),(1,3),(4,2),(4,3)\}$ with each O-D pair having a fixed travel demand. Four test scenarios are considered. They are:

$$\begin{cases} \text{Scenario 1: } Q_{ij}^{pr}=15000,\ Q_{ij}^{tr}=5000 \\ \text{Scenario 2: } Q_{ij}^{pr}=15000,\ Q_{ij}^{tr}=2500 \\ \text{Scenario 3: } Q_{ij}^{pr}=15000,\ Q_{ij}^{tr}=500 \\ \text{Scenario 4: } Q_{ij}^{pr}=15000,\ Q_{ij}^{tr}=0 \end{cases}, \quad \forall (i,j)\in W .$$

We assume that in $D_{a_i}(x)=A_{a_i}+B_{a_i}x$, except that $A_{a_i}=1.5$ for *i* = 1, 7, 13, 15 and 19, and $A_{a_i}=2.5$ for *i* = 4, for remaining arcs $A_{a_i}=2$. $B_{a_i}=6.67\times10^{-4}$ for all arcs. We also assume that the trucks and private vehicles have the same length, that is, in $x_{a_i}(t)=x_{a_i}^{pr}(t)+\beta x_{a_i}^{tr}(t)$, $\beta=1$. We set $\alpha=0.5$ in early/late arrival penalties $F[x]=\alpha x^2$.

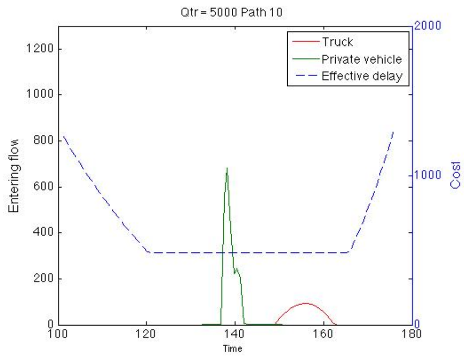
The solution approach is coded in MATLAB 7 and GAMS and solved on Penn State Lion-X system with the following attributes: Intel Xeon E5450 Quad-Core 3.0 GHz and 64GB RAM.

In the rest of this section, Sections 3.3.1, 3.3.2, and 3.3.3 address the following questions respectively.

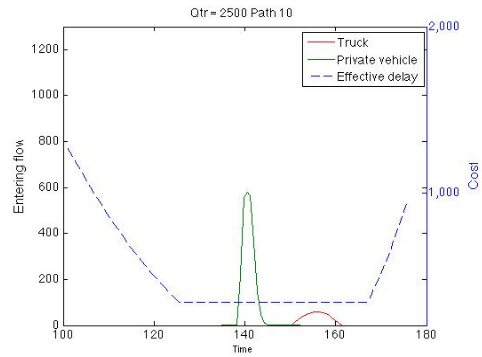
- Will the interaction of freight and personal transportation influence the traffic flow pattern?
- To the truck company, what is the value of incorporating the interaction of freight and personal transportation?
- What managerial insight does the model bring to a MPO?

3.3.1 Traffic Flow Pattern

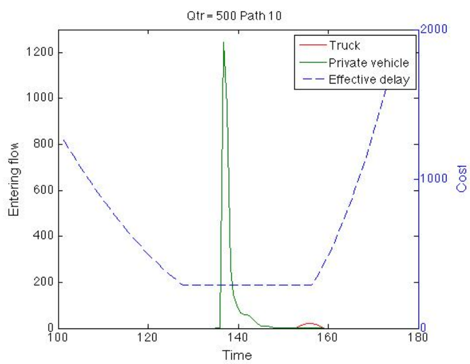
The "optimal" truck flows and equilibrium private vehicle flows are solved by the proposed algorithm. Since there are in total 25 paths that connect the 4 O-D pairs, without loss of generality we only analyze the time-varying traffic flows on Path 10 (Arcs 9, 14, 15 and 18 that connect O-D pair (4, 3)) in each scenario as illustrated in Figure 11.



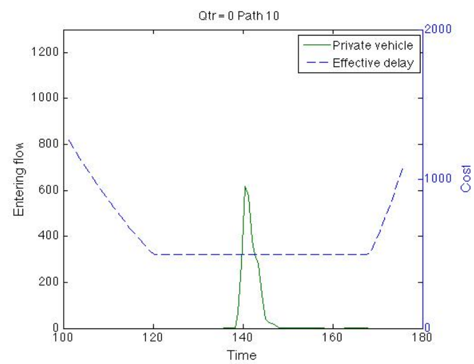
(a)



(b)



(c)



(d)

Figure 11. Dynamic traffic flows on Path 10 in 4 scenarios

In Figure 11, (a), (b), (c) and (d) show the dynamic traffic flows and the effective delay on Path 1 in Scenario 1, 2, 3 and 4, respectively. We can see that in all of these 4 scenarios, traffic flows exist only when the effective delay is at its minimum and the peak of the private vehicle flows occurs at around time 140 which can be considered as the appropriate departure time for private vehicles in order to arrive at the destination at the desired time T_a. From Figure 11, we can clearly identify the interaction of freight and personal transportation. As an example, in Scenario 3 (Figure 11 (c)) when there are in total 500 trucks traveling on the network, the private vehicle flow significantly differs from that in Scenario 4 (Figure 11 (d)) when there is no truck at all. What's more, again in Scenario 3, the peak of private vehicle flow occurs earlier that in Scenario 4. It is not intuitive why the traffic flow pattern in Scenario 3 significantly differs from those in Scenario 1 and 2. However, since the truck company optimizes its transportation cost over the entire network and Figure 11 just illustrates traffic flow pattern on one of the 25 paths of the network, such a result is not surprising.

3.3.2 Comparative Study

By Figure 11, we have demonstrated that there exist interactions between truck and private vehicles even when the number of trucks is relatively small. We would like to further estimate the importance of considering such an interaction in truck scheduling by considering two cases. In Case 1, the truck company ignores the interaction and it simply assumes that the private vehicles will follow DUE without taking into account the truck flows. It estimates the effective delay operator under the regular DUE and uses it as the cost coefficient to optimize truck flows. Let's mark the optimal solution in this case as $\left(\widehat{h}_p^{tr}\right)$. However, as we know, the truck flow will influence the private vehicle flow so that given $\left(\widehat{h}_p^{tr}\right)$, the real DUE flow for private vehicles is different from its estimation and thus the real effective delay operator is not the same as estimated. Thus in Case 1, the real total cost should be calculated using the real effective delay operator. Let's mark the real total cost as z^0. In Case 2, the truck company considers the interaction while optimizing truck flow and the optimal solution will be exactly the solution to the MPCC {(2), (3), (5), (6), (7)}. In Case 2, the minimal total cost is also the real total cost and let's mark it as z^1. We then compare z^0 and z^1 in Scenario 1, 2 and 3 in Table 35 which shows that in all 3 scenarios considering the interaction can help reduce the total cost to the truck company significantly, especially when freight transportation accounts for a considerable portion of total traffic. The computation time is summarized in Table 36 and it is not surprising that in Case 2 the computation time in each scenario is much greater than its counterpart in Case 1 since in Case 1 the original problem is just single-level optimization thus does not involve iterative updates of DUE for private vehicles. However, considering the significant reduction in cost, it is still worth incorporating the interaction of freight and personal transportation for the truck company while making truck schedules.

Table 35. Comparison of total cost

	Scenario 1	Scenario 2	Scenario 3
z^0	1.42×10^7	4.52×10^6	7.99×10^5
z^1	2.58×10^7	7.30×10^6	9.09×10^5
Reduction	44.90%	38.16%	12.12%

Table 36. Comparison of computation time (in second)

	Scenario 1	Scenario 2	Scenario 3
Case 1	2180.46	1760.42	1851.65
Case 2	27408.29	29994.63	63580.18

3.3.3 Braess-Like Paradox in Dynamic Stackelberg Game

So far in this report, we have demonstrated that the interaction of freight and personal transportation should be considered when a truck company schedules its freight transportation in order to save cost. In this subsection, we want to address the concern of a MPO whose objective is to minimize total social cost, the cost to the all owners of private vehicles and the truck company, while ensuring that the travel demand is satisfied. A possible approach is to make a policy to restrict trucks from entering a portion of the network. However, it is not necessarily reducing the total cost since the transportation cost to the truck company may soar. So if it works, we actually come across a Braess-like Paradox: reducing capacity of a network for partial road users who selfishly select their routes can increase overall performance (see Akamatsu and Heydecker (2003) and Lin and Lo (2009) for more details about the dynamic extension of Braess Paradox). Note that since the MPO knows exactly that the truck company and the owners of private vehicles play a Stackelberg game, the problem is actually a tri-level optimization problem. To simplify the formulation and solution of the problem, we explore the existence of such Braess-like paradoxes by a trial-and-error approach. We arbitrarily choose one arc at a time from the network to be blocked for trucks. Then we conduct numerical test to check whether blocking that arc for trucks can reduce the total cost: if yes, then we find the Braess-like paradox and we can stop; if no, we choose another arc and repeat the numerical test and the judgment of result. After several iterations, we find that blocking all the trucks from entering Arc 12 during the time interval of our interest can reduce the total cost (see Figure 12). More details of this policy are summarized in Table 37.

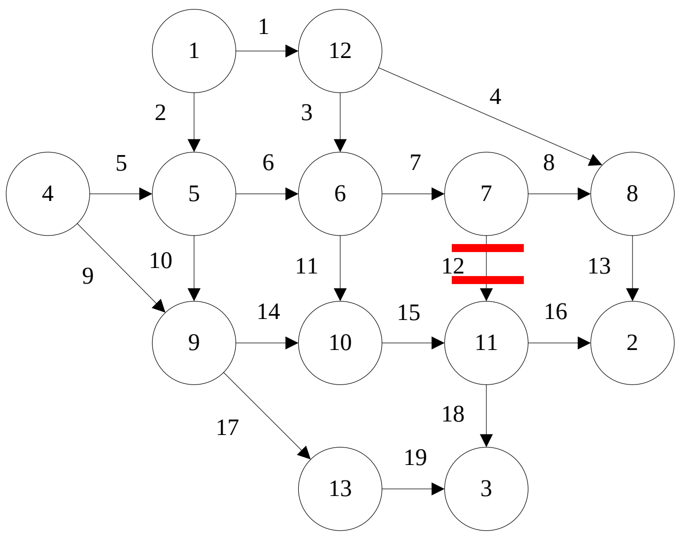


Figure 12. Nguyen-Dupuis network with Arc 12 blocked for all trucks

Table 37. Braess-like Paradox

	Total Cost	Truck Company's Cost	Computation time (in second)
All arcs are accessible	3.16×10^7	4.52×10^6	29994.63
Arc 12 blocked for trucks	3.11×10^7	5.02×10^6	23082.89
Improvement	1.6%	-11.1%	23.0%

From Table 37, we know that the MPO can block trucks from entering Arc 12 to reduce total cost by 1.6%. However, it may increase the truck company's cost by 11.1%. So before the MPO implement such a policy, it should consider the possible obstruction from the truck company and try to balance the increase in social welfare and the loss in the truck company's profit. As an example resolution, the MPO may compensate the truck company for restricting its travel right.

3.4 Conclusion

In this study we model urban freight transportation planning by a dynamic Stackelberg game and formulate the problem as a dynamic MPEC. In particular, we assume that there is a truck company trying to minimize its freight transportation cost which is dependent on its transportation plan and the background traffic such as personal transportation. The model explicitly characterizes the interaction of freight and personal transportation by its lower level problem, that is, DUE with inhomogeneous traffic, and optimizes the truck schedule in the upper level which is an SO problem. To obtain local optimal solutions and achieve efficient computation, we reformulate the MPEC as a MPCC and design a projected gradient algorithm to solve it. Numerical results show that the interaction between different road users - specifically, a trucking company and individuals, exists and is nonnegligible even when the amount of trucks compared to that of private vehicles is small, and demonstrate that significant cost reduction can be achieved if the truck company schedules freight transportation considering this interaction, which supports our concern that in an urban network personal transportation should not be ignored while scheduling freight transportation. Moreover, with extensive numerical tests we find a Braess-like paradox in this dynamic bi-level transportation planning problem which implicates that a MPO may increase social welfare by restricting trucks from entering specific sections of the network during peak hours of a day. At the same time, since the restriction may significantly increase the truck company's cost, the MPO could compensate the truck company in order to smooth the implementation of the restriction.

Some interesting extensions of this study include but not limited to the following: (1) comprehensively investigate the dynamic Braess-like paradox based on the proposed modeling framework and discuss the necessary and sufficient conditions for the paradox to occur; (2) robustify the problem by incorporating uncertain travel demand; (3) model the upper level problem as service network design problem which is more realistic yet more challenging; (4) assume that there exist multiple truck companies competing with each other and study the resulting equilibrium problem with equilibrium constraints (EPEC).

TASK 4 – CONGESTION DERIVATIVES

4.1 Benchmark: Deterministic Bottleneck Model

As a benchmark, we follow Vickrey (1969) by assuming a single bottleneck, such as a bridge or a toll road, between an origin, such as a residential area, and a destination, such as a downtown working area (Figure 13). Every weekday morning, all commuters need to utilize this single bottleneck. Naturally, this single bottleneck is constrained by its capacity s per unit of time, and excessive demand will be queued behind the bottleneck, and will be served first in first out (FIFO). Other than this queuing delay, we assume all other moving times, such as traveling time between the bottleneck and the destination, are negligible without losing any generality.

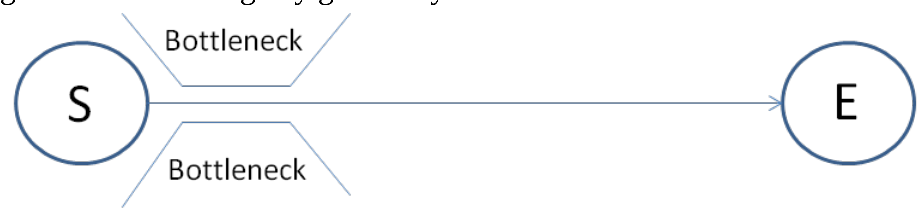


Figure 13. Bottleneck model

We assume there are two groups of commuters, Group 1 and Group 2, to represent the heterogeneity of commuters' backgrounds and preferences. Similar to Arnott et al. (1988), we denote α_i as a unit time value, and β_i (γ_i) as a unit penalty from arriving earlier (later) than the desired time t^*. Consistent with empirical research, let's assume $\gamma_i > \alpha_i > \beta_i$ for Group *i*. In addition, we assume that commuters share the same relative cost of the late arrival schedule delay cost and the early arrival schedule delay cost: $\eta = \gamma_1 / \beta_1 = \gamma_2 / \beta_2$. Arbitrarily, we index the two groups so that $\alpha_1 / \beta_1 \geq \alpha_2 / \beta_2$. With this segmentation, traditionally, Group 1 is characterized as highly paid white-collar workers, and Group 2 as blue-collar workers. Although it is possible that $\alpha_1 / \beta_1 = \alpha_2 / \beta_2$, the solution process will be trivially reduced to the case of homogeneous commuters. Hence, thereafter, we assume $\alpha_1 / \beta_1 > \alpha_2 / \beta_2$. Finally, the commuter's linear cost function is given as

$$C_i(t) = \begin{cases} \alpha_i \dfrac{q(t)}{s} + \beta_i [t^* - (t + \dfrac{q(t)}{s})] + u(t), \text{ for } t \in [t_s, t_o] \\ \alpha_i \dfrac{q(t)}{s} + \gamma_i [(t + \dfrac{q(t)}{s}) - t^*] + u(t), \text{ for } t \in [t_o, t_e] \end{cases}$$

For convenience, we summarize our notations as follows.

s :	bottleneck capacity;
N_i :	total number of commuters for the *i*th group;
α_i :	unit time value for the *i*th group;
β_i :	unit time cost of schedule delay for arriving earlier for the *i*th group;
γ_i :	unit time cost of schedule delay for arriving later for the *i*th group;
ξ_i :	unit volatility penalty for the *i*th group;
η :	γ_i / β_i;

δ_i: $\beta_i\gamma_i/(\beta_i+\gamma_i)$;

t^*: preferred arrival time;

t_s: time at which the queue starts;

t_e: time at which the queue ends;

t_o: time at which if an commuter departures, then he/she will arrive the destination at t^*;

$u(t)$: road toll at time *t*;

$q(t)$: queue length at time *t*;

$r_i(t)$: departure rate at time *t* for the *i*th group.

Note that the deterministic bottleneck model with two groups of heterogeneous commuters has been analyzed in Arnott et al. (1988). Hence, to avoid duplication, we will skip technique details and only summarize some key results as benchmarks in Section 4.1.1 and Section 4.1.2.

4.1.1 Deterministic Model: without Tolls

In general, the equilibrium condition among commuters can be stated as follows: *every commuter is unable to find another departure time to reduce his/her travel cost when the system is in the equilibrium*. Futhermore, for simplicity, we only consider a pure strategy equilibrium among commuters. If there is no toll, that is, $u(t)=0$, then we will have the equilibrium departure behavior as illustrated by Figure 14 and the queue length as illustrated by Figure 15.

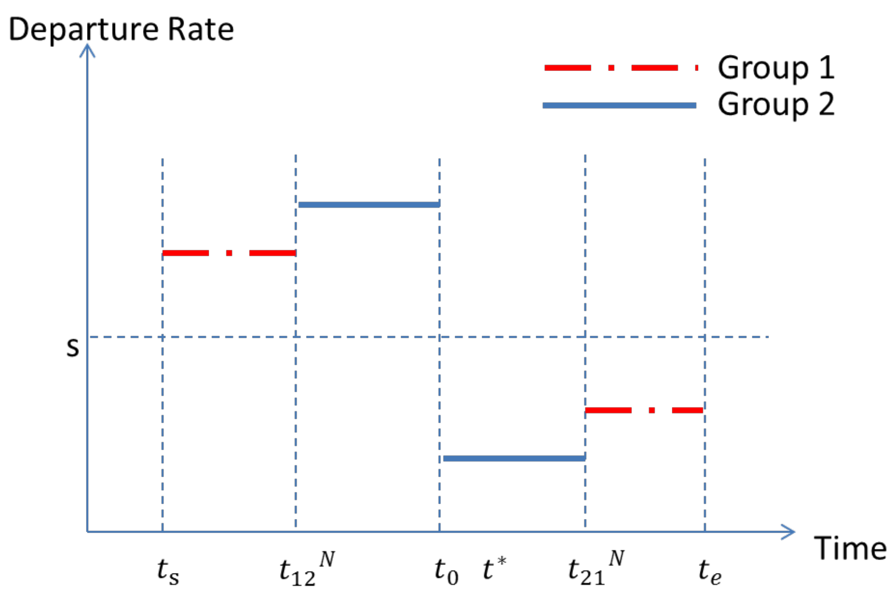


Figure 14. Departure rate over time without tolls

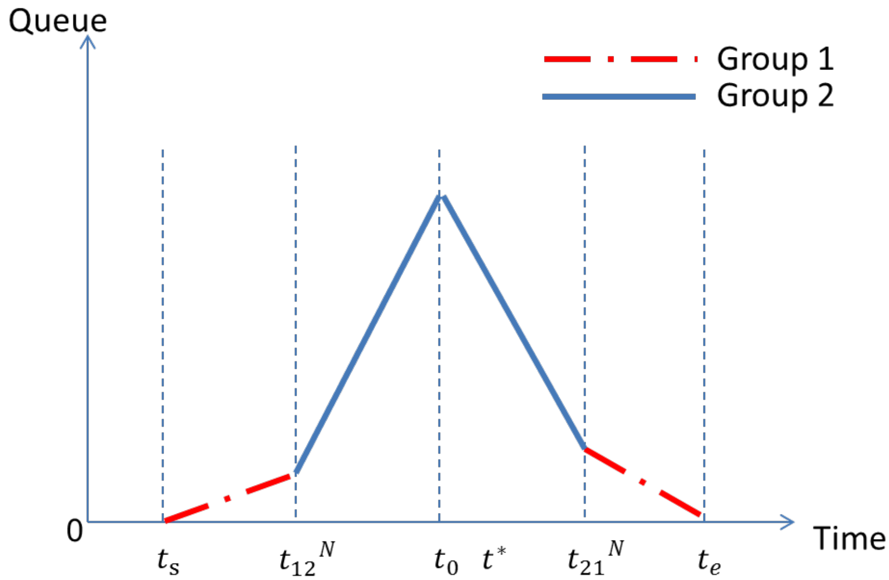


Figure 15. Queue length over time without tolls

Obviously, at equilibrium, Group 1 will depart at two ends and Group 2 will depart in the middle of the time horizon. Specifically, Group 1 only departs during $[t_s, t_{12}{}^N]$ and $[t_{21}{}^N, t_e]$, while Group 2 continuously travels in $[t_{12}{}^N, t_{21}{}^N]$. The critical time points are

$$\begin{cases} t_s = t^* - \dfrac{\eta(N_1+N_2)}{(1+\eta)s} \\ t_{12}{}^N = t^* - \dfrac{\eta}{(1+\eta)}\dfrac{N_2}{s} - \dfrac{\beta_1}{\alpha_1}\dfrac{\eta}{(1+\eta)}\dfrac{N_1}{s} \\ t_0 = t^* - \dfrac{\beta_2}{\alpha_2}\dfrac{\eta}{(1+\eta)}\dfrac{N_2}{s} - \dfrac{\beta_1}{\alpha_1}\dfrac{\eta}{(1+\eta)}\dfrac{N_1}{s}, \\ t_{21}{}^N = t^* + \dfrac{1}{(1+\eta)}\dfrac{N_2}{s} - \dfrac{\beta_1}{\alpha_1}\dfrac{\eta}{(1+\eta)}\dfrac{N_1}{s} \\ t_e = t^* + \dfrac{(N_1+N_2)}{(1+\eta)s} \end{cases}$$

and the costs for the Group 1 and Group 2 can be shown to be

$$\begin{cases} C_1 = \dfrac{\delta_1(N_1+N_2)}{s} \\ C_2 = \dfrac{\alpha_2}{\alpha_1}\delta_1\dfrac{N_1}{s} + \delta_2\dfrac{N_2}{s} \end{cases}.$$

Hence, the total social cost, TC, will be:

$$TC^N = N_1C_1 + N_2C_2 = \delta_1\frac{N_1{}^2}{s} + (1+\frac{\alpha_2}{\alpha_1})\delta_1\frac{N_1N_2}{s} + \delta_2\frac{N_2{}^2}{s},$$

which can be further separated into two pieces: the total queuing cost, TQC:

$$TQC^N = \int_{t_s}^{t_{12}^N} \alpha_1(\frac{q(t)}{s})sdt + \int_{t_{12}^N}^{t_0} \alpha_2(\frac{q(t)}{s})sdt + \int_{t_0}^{t_{21}^N} \alpha_2(\frac{q(t)}{s})sdt + \int_{t_{21}^N}^{t_e} \alpha_1(\frac{q(t)}{s})sdt$$
$$= \delta_1 \frac{N_1^2}{2s} + \delta_1 \frac{\alpha_2}{\alpha_1}\frac{N_1 N_2}{s} + \delta_2 \frac{N_2^2}{2s}$$

and the total delay cost, TDC:

$$TDC^N = TC^N - TQC^N = \delta_1 \frac{N_1^2}{2s} + \delta_1 \frac{N_1 N_2}{s} + \delta_2 \frac{N_2^2}{2s}.$$

Lemma 2: Without uncertainty and dynamic tolls, Group 1 departs at two ends of the time horizon, and Group 2 departs in the middle.

4.1.2 Deterministic Model: with an Optimal Toll

With an omniscient social planner, we can show that, by adopting an approperate dynamic toll, all queuing costs can be eliminated and the departure pattern will be shaped to minimize the total social cost. Given this result, without any queue, the only cost matters for Group 1 and Group 2 commuters will be the schedule delay cost. Hence, the total social cost can be minimized if the group with higher delay cost commutes closer to the preferred arrival time, t^*, than the other group.

Without loss of generality, let's assume $\beta_2 > \beta_1$, that is, the unit time cost of the schedule delay for arriving earlier of Group 2 is higher than that of Group 1. The other case can be analyzed identically, so is ignored in this study. Under this assumption, we can show that Group 2 should travel in the middle of the time horizon, close to t^*, while Group 1 departures at two far ends. Obviously, both groups have a combined departure rate of s per unit of time to eliminate the queue.

Group 2 departs from time t_{12}^O to t_{21}^O, and Group 1 travels at $[t_s, t_{12}^O]$ and $[t_{21}^O, t_e]$. The switching times between Group 1 and Group 2 are:

$$\begin{cases} t_{12}^O = t^* - \dfrac{\delta_1 N_2}{\beta_1 s} = t^* - \dfrac{\eta N_2}{(1+\eta)s} \\ t_{21}^O = t^* + \dfrac{\delta_1 N_2}{\gamma_1 s} = t^* + \dfrac{N_2}{(1+\eta)s} \end{cases}$$

Similar to the Section 4.1.1, we can easily calculate the individual commuter's cost for each group:

$$\begin{cases} \overline{C}_1 = \delta_1 \dfrac{N_1}{s} + \delta_1 \dfrac{N_2}{s} \\ \overline{C}_2 = \delta_1 \dfrac{N_1}{s} + \delta_2 \dfrac{N_2}{s} \end{cases}.$$

In order to sustain this equilibrium, we must carefully impose tolls so that no commuter will have incentive to deviate from this socially optimal solution. Using $\overline{C}_1$ and $\overline{C}_2$, as shown in Figure 16, we can easily verify that this socially optimal solution holds, if the following optimal dynamic toll is adopted:

$$u^*(t) = \begin{cases} 0, \text{ for } t \in (-\infty, t_s] \\ \bar{C}_1 - \beta_1(t^* - t), \text{ for } t \in [t_s, t_{12}{}^O] \\ \bar{C}_2 - \beta_2(t^* - t), \text{ for } t \in [t_{12}{}^O, t^*] \\ \bar{C}_2 - \gamma_2(t - t^*), \text{ for } t \in [t^*, t_{21}{}^O] \\ \bar{C}_1 - \gamma_1(t - t^*), \text{ for } t \in [t_{21}{}^O, t_e] \\ 0, \text{ for } t \in [t_e, \infty) \end{cases}$$

Hence, the Total Social Cost, TC, will be:

$$TC^T = TDC^T = \left(\int_{t_s}^{t_{12}{}^O} \beta_1(t^* - t)dt + \int_{t_{12}{}^O}^{t^*} \beta_2(t^* - t)dt + \int_{t^*}^{t_{21}{}^O} \gamma_2(t - t^*)dt + \int_{t_{21}{}^O}^{t_e} \gamma_1(t - t^*)dt \right) s$$

$$= \delta_1 \frac{N_1{}^2}{2s} + \delta_1 \frac{N_1 N_2}{s} + \delta_2 \frac{N_2{}^2}{2s}$$

And the total social welfare improvement under the optimal dynamic toll will be:

$$\Delta TC = TC^N - TC^T = \delta_1 \frac{N_1{}^2}{2s} + \frac{\alpha_2}{\alpha_1} \delta_1 \frac{N_1 N_2}{s} + \delta_2 \frac{N_2{}^2}{2s}.$$

Lemma 3: Without uncertainty, under the optimal dynamic toll, Group 1 will depart at the two ends of the time horizon, and Group 2 will travel in the middle. Furthermore, the dynamic toll can eliminate all queues and, hence, reduce the total social cost.

Interestingly, the optimal dynamic toll will not influence the cost of Group 1, as $\bar{C}_1 = C_1$. However, Group 2 will be better off if $\alpha_2 > \alpha_1$ and worse off if $\alpha_2 < \alpha_1$.

Corollary 1: With the optimal dynamic toll, Group 1 is equally well off while Group 2 is better/worse off if its unit time value is greater/less than Group 1's.

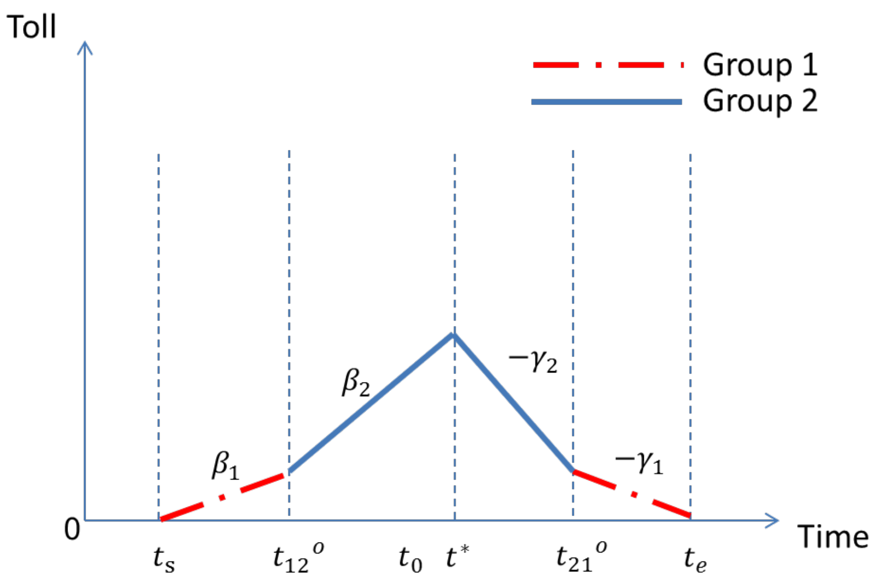


Figure 16. The optimal toll over time

4.2 Stochastic Bottleneck Model: an Introduction

From this section on, we will introduce stochasticity and commuter's risk preference into a single bottleneck model. The exogenous uncertainty comes from various sources, such as a toll pricing uncertainty or a travel time uncertainty (Chen 2010, Friesz et al. 2007, Halvorson et al. 2006, Yao et al. 2010, Yin and Lou 2009, and etc.). As argued in Friesz et al. (2007), we can aggregate those uncertainties and express them in terms of an underlying asset's price uncertainty. For detailed discussions, please refer to Yao et al (2010). Therefore, we will focus our attentions on a stochastic toll $u(t)$ which follows a general stochastic process.

For an arbitrary commuter, under a stochastic toll, the time line is described as follows: the arbitrary commuter will first decide whether he/she wants to purchase a congestion derivative, and pay the price if an agreement is made; then he/she will calculate his/her utility and choose a departure time to minimize his/her travel cost; next, uncertainty will be realized but unobservable until commuter arrives at the bottleneck; finally, the third party will collect the toll according to the stochastic toll scheme. Note that commuters cannot change route or reserve their vehicles when they observe the realized toll upon the bottleneck, but they are able to choose to or not to exercise their derivatives if those derivatives are in the form of an option instead of a binding contract.

Furthermore, we model commuter's risk-averse behavior by adopting the mean-variance utility model (Chen (2010), Li et al. (2009), Yao et al. (2010)). In particular, besides the usual travel cost, we introduce an additional volatility penalty term $\xi_i\sqrt{Var(u(t))}$ to reflect the disutility from uncertainty for Group *i* (for more discussion about this volatility penalty, please refer to Yao et al. (2010)). Hence, the commuter's cost function can be expressed as follows:

$$C_i(t) = \begin{cases} E\left[\alpha_i \dfrac{q(t)}{s} + \beta_i[t^* - (t + \dfrac{q(t)}{s})] + u(t)\right] + \xi_i\sqrt{Var(u(t))}, \text{ for } t \in [t_s, t_o] \\ E\left[\alpha_i \dfrac{q(t)}{s} + \gamma_i[(t + \dfrac{q(t)}{s}) - t^*] + u(t)\right] + \xi_i\sqrt{Var(u(t))}, \text{ for } t \in [t_o, t_e] \end{cases}. \tag{1}$$

In order to include more general types of stochasticity and illustrate the advantage of congestion derivatives, we introduce two families of stochasticity: additive stochasticity and multiplicative stochasticity. Specifically, in Section 4.3, additive stochasticity is offered to answer the questions of *how stochasticity will influence the commuters' departure equilibria* and *why congestion derivatives can be helpful to restore socially optimal equilibrium*. In Section 4.4, a more complicated form of stochasticity, multiplicative stochasticity, will be introduced to show *how devastative the effect will be when commuters have risk preference*. Moreover, in addition to previous questions, although the general commuters' equilibria are extremely difficult, if not impossible, to analyze analytically for multiplicative stochasticity, we *provide a general iterative procedure of identifying an equilibrium* and provide an analytical solution under some conditions. Furthermore, we show *how powerful congestion derivatives are in terms of reducing the total social cost*. At last, for more general stochastic processes and congestion derivatives, where analytical solutions are not available, we developed a numerical model to explore more general results in Section 4.5.

Meanwhile, from an implementation point of view, in order to answer the question of *do we need an omniscient social planner to achieve socially optimum*, we consider and compare two distribution channels of congestion derivatives, the direct central planner channel and the market-based mechanism in both Section 4.3 and Section 4.4.

4.3 Stochastic Bottleneck Model: Additive Stochasticity

In this section, we assume that the optimal toll is subject to an additive random shock, ε. In other words, the realized toll is the summation of the optimal toll under deterministic case and the random term:

$$u(t) = u^*(t) + \varepsilon = \begin{cases} \varepsilon, \text{ for } t \in (-\infty,\ t_s] \\ \bar{C}_1 - \beta_1(t^* - t) + \varepsilon, \text{ for } t \in [t_s,\ t_{12}{}^O] \\ \bar{C}_2 - \beta_2(t^* - t) + \varepsilon, \text{ for } t \in [t_{12}{}^O,\ t^*] \\ \bar{C}_2 - \gamma_2(t - t^*) + \varepsilon, \text{ for } t \in [t^*,\ t_{21}{}^O] \\ \bar{C}_1 - \gamma_1(t - t^*) + \varepsilon, \text{ for } t \in [t_{21}{}^O,\ t_e] \\ \varepsilon, \text{ for } t \in [t_e,\ \infty) \end{cases}.$$

More specifically, we assume ε is time independent and identically distributed with a probability density function (PDF) $f(\varepsilon)$, mean $E(\varepsilon)$, and variance $Var(\varepsilon)$. $u^*(t)$ is the optimal toll in the deterministic case.

The micro-foundations for additive stochasticity can be contributed to either forecasting error or travel delay. In Chen (2010), author adopts the form of the additive cost because the travel delay can be generalized from multiple sources, such as weather or accident. In addition, this additive stochasticity can directly come from mismatching of forecasted demand and realized demand (For more detailed discussion, please refer to Yao et al. (2010)).

For consistency and without losing any generality, we follow the assumption in previous sections by setting $\beta_2 > \beta_1$.

4.3.1 Without Congestion Derivatives

Since $E\left(u\left(t\right)\right) = u\left(t\right)^* + E\left(\varepsilon\right)$ and $Var(u\left(t\right)) = Var(\varepsilon)$, the individual cost experienced by commuters in equation (1) can be stated as:

$$C_i(t) = \begin{cases} \alpha_i \dfrac{q(t)}{s} + \beta_i[t^* - (t + \dfrac{q(t)}{s})] + u(t)^* + E\left(\varepsilon\right) + \xi_i\sqrt{Var(\varepsilon)}, \text{ for } t \in [t_s{}^S, t_o] \\ \alpha_i \dfrac{q(t)}{s} + \gamma_i[(t + \dfrac{q(t)}{s}) - t^*] + u(t)^* + E\left(\varepsilon\right) + \xi_i\sqrt{Var(\varepsilon)}, \text{ for } t \in [t_o{}^S, t_e] \end{cases}. \quad (2)$$

Observe that adding this stochasticity will not change the equilibrium analysis we have articulated in Section 4.1, but will only add an additional cost term, $E(\varepsilon) + \xi_i\sqrt{Var(\varepsilon)}$, which is independent of time *t*, to each commuter. Thus, the first order condition for commuter's cost function is unchanged under addtive stochasticity. Consequently, the commuters' equilibria departure behaviors under this type of stochastic toll will be identical to that in the deterministic case. Hence, under the additive stochastic toll, the individual cost for Group 1 and Group 2 are:

$$\begin{cases} \bar{C}_1^{add} = \bar{C}_1 + E(\varepsilon) + \xi\sqrt{Var(\varepsilon)} = \delta_1 \frac{N_1}{s} + \delta_1 \frac{N_2}{s} + E(\varepsilon) + \xi_1\sqrt{Var(\varepsilon)} \\ \bar{C}_2^{add} = \bar{C}_2 + E(\varepsilon) + \xi\sqrt{Var(\varepsilon)} = \delta_1 \frac{N_1}{s} + \delta_2 \frac{N_2}{s} + E(\varepsilon) + \xi_2\sqrt{Var(\varepsilon)} \end{cases}.$$

The expected total social cost without congestion derivative will be:

$$\begin{aligned} TC^{AST} &= \delta_1 \frac{N_1^2}{2s} + \delta_1 \frac{N_1 N_2}{s} + \delta_2 \frac{N_2^2}{2s} + (N_1 + N_2)E(\varepsilon) + (N_1\xi_1 + N_2\xi_2)\sqrt{Var(\varepsilon)} \\ &= TC^T + (N_1 + N_2)E(\varepsilon) + (N_1\xi_1 + N_2\xi_2)\sqrt{Var(\varepsilon)} \end{aligned}.$$

Hence, the preceding analysis also validates the following lemma.

Lemma 4: The commuter's equilibrium departure behavior will be the same with or without the additive stochasticity.

If we compare the individual cost under the additive stochasticity and that in deterministic case, we can easily get the following corollary.

Corollary 2: If both groups are risk-averse, that is $\xi_i > 0,\ i = 1,2$, then commuters in both groups will have higher costs under the additive stochastic toll than under the deterministic toll. The larger the degree of risk aversion is, the higher the costs will be.

4.3.2 With Congestion Derivatives

In this section, we distinguish between two cases: the derivative issuer is a central planner or is a market. The importance of this distinction is that the central planner may not require Budget-Balance (BB) or No Outside Subsidies (NOS) constraints. In other words, in the former case, where the derivative is priced by a central planner, this central planner's objective is to maximize the total social welfare so that even if this social welfare maximization plan requires the central planner to net subsidy or tax commuters, it should be able to carry out this plan. However, in the later case, the market-based mechanism, the derivative price is determined solely by market demand-supply relationship. Within this derivative market, the issuers and traders are profit-seeking individuals, and the market clearing price generally is an no-arbitrage price, so BB and NOS constraintsmust be satisfied strictly.

The purpose of this discussion is twofold: to investigate whether the central planner's involvement can be beneficial to sociaty, and to explore whether the pure market-based mechanism benefits the sociaty at a similar level.

If the central planner behaves in the interest of society and has better information than the private section firms, who collect the toll to recover their infrasturcture investments, then it will try to reduce the total social cost by reducing commuter's risk premium while leaving departure behaviors unchanged.

One way to achieve this objective is to offer a forward contract at a striking price of $u^*(t)$ which is equal to or below $E(\varepsilon)$. In this case, the commuter will have an incentive to purchase this forward contract and eliminate the risk premium completely without changing his/her departure behavior. So, in other words, this forward contract garrantees the ex post equilibrium to be socially optimal (Note that this analysis involves equilibrium analysis with an incentive compatible constraint, which requires that the rational commuter has incentive to participate in buying those derivatives by taking into account of the ex post equilibrium, which is the commuter's departure equilibrium after the purchasing decision was made and the cost of forward contract has been salvaged).

Now let's focus on the incentive compatible constraint. For an arbitrary commuter, if he/she purchases forward contract, his/her utility will be less than or equal to $\bar{C}_i + E(\varepsilon)$; on the other hand, if he/she deviates and decides not to purchase, then he/she will still keep his/her departure behavior as the social optimum but ends up with a utility $\bar{C}_i + E(\varepsilon) + \xi\sqrt{Var(\varepsilon)}$. Hence, the incentive compatible constraint for all commuters will be satisfied, and, hence, the ex ante equilibrium, the commuters' equilibrium before purchasing decision is made, is also socially optimal. The individual cost of each group will be reduced to:

$$\begin{cases} \bar{C}_1^{add,cs} = \bar{C}_1 + E(\varepsilon) \le \bar{C}_1^{add} \\ \bar{C}_2^{add,cs} = \bar{C}_2 + E(\varepsilon) \le \bar{C}_2^{add} \end{cases}.$$

Lemma 5: With the additive stochasticity and a central subsidy, the commuter's equilibrium departure behavior will be the same as the one in the deterministic case.

Corollary 3: With the presence of the additive stochastic toll, if both groups are risk-averse, that is $\xi_i > 0$ for $i = 1, 2$, then both groups will be better off with a forward contract than without. The group with a greater degree of risk aversion will benefit more from the forward contract.

If the central planner can not swiftly or responsively adjust its decisions, then we try to find out whether a market-based mechanism can be as effective as the central planner. Similarly, we assume that there exists a makert for issueing and trading the forward contract. In the market, naturally, the forward contract price will equal to $E\left[u(t) - u^*(t)\right]$, the no-arbitrage price.

With this no-arbitrage price, we can show that both the ex ante and the ex post equilibrium are also socially optimal in the same way as we showed in the central planner's case. Moreover, the individual cost of each group will be the same as that in the case with the central planner.

Theorem 5: With the addititive stochasiticity, both the central planner and the market-based mechanism can eliminate the externalities from stochasiticity and risk aversion behavior by reducing risk premium. Moreover, if both groups are risk-averse, that is $\xi_i > 0$ for $i = 1, 2$, then both groups will be better off and the group with a greater degree of risk aversion will benefit more.

4.4 Stochastic Bottleneck Model: Multiplicative Stochasticity

In this section, we will assume that the actual toll is subject to a multiplicative stochasticity. Specifically, we incorporate the time-invariant multiplicative stochasticity ε, which is independent and identically distributed with a PDF $f(\varepsilon)$, mean $E(\varepsilon)$, and variance $Var(\varepsilon)$. This multiplicative stochasticity may come from tax uncertainty or some other sources (Yao et al. (2010)). Thus, the actual toll can be writen as:

$$u(t)=(1+\varepsilon)u^*(t)=\begin{cases}0,\ \text{for } t\in(-\infty,\ t_s]\\(1+\varepsilon)\left(\bar{C}_1-\beta_1(t^*-t)\right),\ \text{for } t\in[t_s,\ t_{12}{}^{O}]\\(1+\varepsilon)\left(\bar{C}_2-\beta_2(t^*-t)\right),\ \text{for } t\in[t_{12}{}^{O},\ t^*]\\(1+\varepsilon)\left(\bar{C}_2-\gamma_2(t-t^*)\right),\ \text{for } t\in[t^*,\ t_{21}{}^{O}]\\(1+\varepsilon)\left(\bar{C}_1-\gamma_1(t-t^*)\right),\ \text{for } t\in[t_{21}{}^{O},\ t_e]\\0,\ \text{for } t\in[t_e,\ \infty)\end{cases}.$$

For analytical tractability, we make the following assumption in this section:

Assumption 1: $\alpha_1=n\alpha_2=n\alpha$, $\beta_1=n\beta_2=n\beta$, $\gamma_1=n\gamma_2=n\gamma$, and $\xi_1=m\xi_2=m\xi$, where $n,m>1$.

Without this assumption, the departure equilibria may untractable, but our insights will still hold (Please check Section 4.5 for numerical examples on more general settings). Moreover, the analysis for finding the equilibria departure behavior will be identical, although more tedious, for any general mutiplicative stocahsticity and commuter's cost parameters. Hence, we use this assumption to illustrate the iterative method of finding an equilbrium.

This assumption essentially means that: (1) the white collar worker has higher time value and this proportional higher time value is consistent between waiting time and schedule delays; (2) the white collar worker will be more risk-averse than the blue collar worker

Accordingly, denote $\delta_2=\dfrac{\beta\gamma}{\beta+\gamma}=\dfrac{\beta\eta}{1+\eta}=\delta$ and $\delta_1=\dfrac{n\beta\gamma}{\beta+\gamma}=\dfrac{n\beta\eta}{1+\eta}=n\delta$.

Under Assumption 1, considering the case with the optimal deterministic toll, without stochasticity, we will have the equilibrium departure behavior as illustrated by Figure 17.

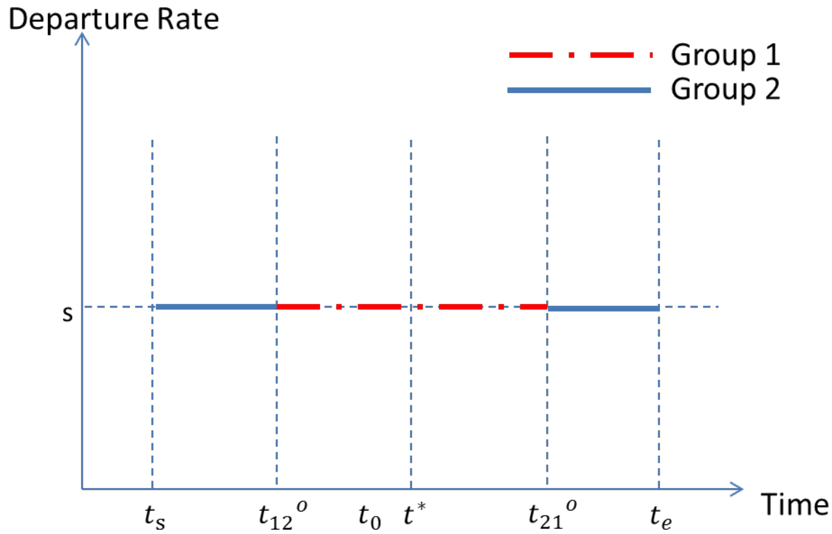


Figure 17. Departure rate over time with the deterministic optimal toll

where $t_s = t^* - \delta(N_1 + N_2)/\beta s$, $t_{12}{}^O = t_1{}^O = t^* - \delta N_1/\beta s$, $t_0 = t^*$, $t_{21}{}^O = t_2{}^O = t^* + \delta N_1/\gamma s$, and $t_e = t^* + \delta(N_1 + N_2)/\gamma s$.

4.4.1 Without Congestion Derivatives

When the multiplicative stochasticity is introduced, the departure equilibrium will deviate from the socially optimal equilibrium.To begin with, we will solve the commuters' departure equilibrium under a stochastic toll by the following iterative method. Firstly, we will conjecture a possible commuters' departure behaviors; then the critical times and departure rates will be calculated based on our conjecture; at last we will check whether the equilibrium condition holds under our conjecture: if equilibrium condition holds, then we are done; otherwise a new conjecture will be proposed and we will start from the first step. One crucial part of adopting this iterative method is selecting an approperate initial conjecture. If the intial conjecture is verifiable, then we are done. Otherwise, we need to propose additional conjecture to go through the verification process, which is very time consuming.

To illustrate this iterative method, let's consider the case with a multiplicative stochastic toll, but without congestion derivatives first. To simplify the analysis but without losing any generality, we assume $E(\varepsilon) = 0$. In order to solve for the equilibrium departure rate, we first conjecture the departure behavior as shown in Figure 18 and critical times as $t_{1s}{}^M \le t_s \le t_{1e}{}^M \le t_1{}^O \le t^* \le t_2{}^O \le t_{2s}{}^M \le t_e \le t_{2e}{}^M$.

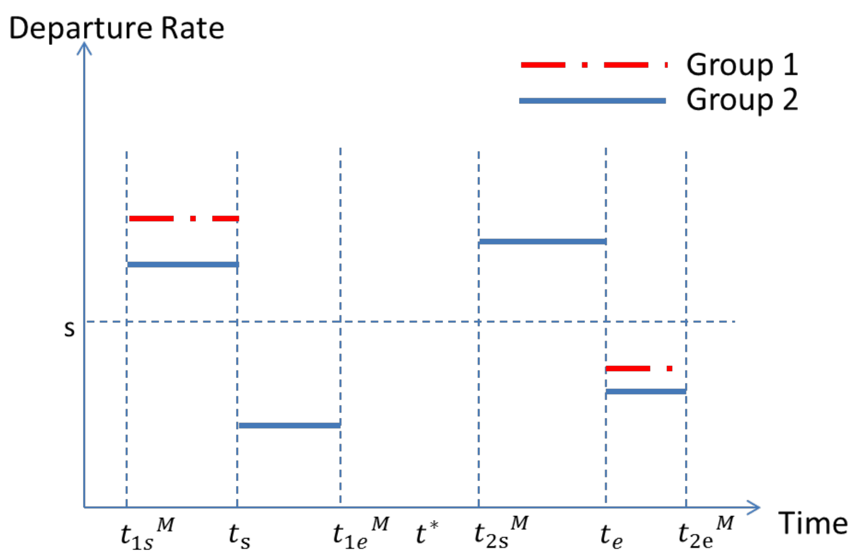


Figure 18. Departure rate over time with multiplicative stochasticity

Accordingly, the individual cost for two groups of commuters will be:

$$C_1(t) = \begin{cases} n\alpha \dfrac{q(t)}{s} + n\beta[t^* - (t + \dfrac{q(t)}{s})], \text{ for } t \in [t_{1s}{}^M, t_s] \\ n\alpha \dfrac{q(t)}{s} + n\gamma[(t + \dfrac{q(t)}{s}) - t^*], \text{ for } t \in [t_e, t_{2e}{}^M] \end{cases}$$

$$C_2(t)=\begin{cases}\alpha\dfrac{q(t)}{s}+\beta[t^*-(t+\dfrac{q(t)}{s})], \text{ for } t\in[t_{1s}{}^M,t_s]\\ \alpha\dfrac{q(t)}{s}+\beta[t^*-(t+\dfrac{q(t)}{s})]+\left[\delta\dfrac{N_1}{s}+\delta\dfrac{N_2}{s}-\beta(t^*-t)\right](1+\xi\sqrt{Var(\varepsilon)}), \text{ for } t\in[t_s,t_{1e}{}^M]\\ \alpha\dfrac{q(t)}{s}+\gamma[(t+\dfrac{q(t)}{s})-t^*]+\left[\delta\dfrac{N_1}{s}+\delta\dfrac{N_2}{s}-\gamma(t-t^*)\right](1+\xi\sqrt{Var(\varepsilon)}), \text{ for } t\in[t_{2s}{}^M,t_e]\\ \alpha\dfrac{q(t)}{s}+\gamma[(t+\dfrac{q(t)}{s})-t^*], \text{ for } t\in[t_e,t_{2e}{}^M]\end{cases}$$

For a sustainable equilibrium, the FOC of $C_i(t)$ should all be zero which results in:

$$\begin{cases}r_1+r_2=\dfrac{\alpha}{\alpha-\beta}s \quad \text{(FOC of group 1 and 2) where } t\in[t_{1s}{}^M,t_s]\\ r_2=(1-\dfrac{\beta\xi\sqrt{Var(\varepsilon)}}{\alpha-\beta})s \quad \text{(FOC of group 2) where } t\in[t_s,t_{1e}{}^M]\\ r_2=(1+\dfrac{\gamma\xi\sqrt{Var(\varepsilon)}}{\alpha+\gamma})s \quad \text{(FOC of group 2) where } t\in[t_{2s}{}^M,t_e]\\ r_1+r_2=\dfrac{\alpha}{\alpha+\gamma}s \quad \text{(FOC of group 1 and 2) where } t\in[t_e,t_{2e}{}^M]\end{cases}$$

Due to the non-negativity constraint of the departure rate, from the departure rate within $[t_s,t_{1e}{}^M]$, we have an upper bound for ξ:

$$\xi\le\frac{\alpha-\beta}{\beta\sqrt{Var(\varepsilon)}}.$$

Furthermore, the sum of the total departures in the first time frame, between $t_{1s}{}^M$ and $t_{1e}{}^M$, should equal to the sum of the corresponding total arrivals:

$$\frac{\alpha}{\alpha-\beta}s\ (t_s-t_{1s}{}^M)+(1-\frac{\beta\xi\sqrt{Var(\varepsilon)}}{\alpha-\beta})s(t_{1e}{}^M-t_s)=s(t_{1e}{}^M-t_{1s}{}^M).$$

Similarly, the total departure for the second time frame, between $t_{2s}{}^M$ and $t_{2e}{}^M$, will be identical to the total corresponding arrivals as well:

$$\frac{\alpha}{\alpha+\gamma}s\ (t_{2e}{}^M-t_e)+(1+\frac{\gamma\sqrt{Var(\varepsilon)}}{\alpha+\gamma})s(t_e-t_{2s}{}^M)=s(t_{2e}{}^M-t_{2s}{}^M).$$

Note that the above two equations also guarantee that all queues will be cleared at time $t_{1e}{}^M$ and $t_{2e}{}^M$. Also, in equilibrium, the cost of the last commuter of Group 2 at the end of the first time frame should equal to the cost of the last commuter of Group 2 at the end of the second time frame:

$$\beta[t^*-t_{1e}{}^M]+\left[\delta\frac{N_1}{s}+\delta\frac{N_2}{s}-\beta(t^*-t_{1e}{}^M)\right](1+\xi\sqrt{Var(\varepsilon)})=\gamma[t_{2e}{}^M-t^*].$$

At last, we have the flow conservation constraint:

$$\left[t_{2e}{}^M-t_{2s}{}^M+t_{1e}{}^M-t_{1s}{}^M\right]s=N_1+N_2.$$

Hence, solve the above equations, we have:

$$\begin{cases} t_{1s}{}^{M} = t^{*} - \dfrac{1+2\xi\sqrt{Var(\varepsilon)}}{1+\xi\sqrt{Var(\varepsilon)}}\dfrac{\eta}{1+\eta}\dfrac{N_1+N_2}{s} \\ t_{1e}{}^{M} = t^{*} - \dfrac{\xi\sqrt{Var(\varepsilon)}}{1+\xi\sqrt{Var(\varepsilon)}}\dfrac{\eta}{1+\eta}\dfrac{N_1+N_2}{s} \\ t_{2s}{}^{M} = t^{*} + \dfrac{\xi\sqrt{Var(\varepsilon)}}{1+\xi\sqrt{Var(\varepsilon)}}\dfrac{1}{1+\eta}\dfrac{N_1+N_2}{s} \\ t_{2e}{}^{M} = t^{*} + \dfrac{1+2\xi\sqrt{Var(\varepsilon)}}{1+\xi\sqrt{Var(\varepsilon)}}\dfrac{1}{1+\eta}\dfrac{N_1+N_2}{s} \end{cases}.$$

In addition, to ensure that Group 1 will not choose to depart between $t_{1e}{}^{M}$ and $t_{2s}{}^{M}$, we have the following constraints:

$$\begin{cases} C_1(t_{1s}{}^{M}) \le C_1(t_{1e}{}^{M}) \\ C_1(t_{1s}{}^{M}) \le C_1(t_1^{O}) \end{cases}$$

which lead to the following two inequalities on m:

$$\begin{cases} m \ge \dfrac{n\beta(t_{1e}{}^{M} - t_{1s}{}^{M})}{\left[\delta\dfrac{N_1}{s} + \delta\dfrac{N_2}{s} - \beta(t^{*} - t_{1e}{}^{M})\right]}\dfrac{1}{\xi\sqrt{Var(\varepsilon)}} - \dfrac{1}{\xi\sqrt{Var(\varepsilon)}} \\ m \ge \dfrac{n\beta(t_1^{O} - t_{1s}{}^{M})}{\left[\delta\dfrac{N_2}{s} + n\delta\dfrac{N_1}{s} - n\beta(t^{*} - t)\right]}\dfrac{1}{\xi\sqrt{Var(\varepsilon)}} - \dfrac{1}{\xi\sqrt{Var(\varepsilon)}} \end{cases}.$$

Obviously, there exists a positive *m*, which satisfies the above inequalities. Simple calculation can show that those critical time boundaries, $t_{1s}{}^{M}, t_{1e}{}^{M}, t_{2s}{}^{M}$, and $t_{2e}{}^{M}$, satisfy our hypothesis.

Still, we need to show that $t_{1e}{}^{M} \le t_1^{O}$ and $t_2^{O} \le \mathrm{t}_{2s}{}^{M}$. As

$$\begin{cases} t_1^{O} - t_{1e}{}^{M} = \dfrac{1}{1+\xi\sqrt{Var(\varepsilon)}}\dfrac{\eta}{1+\eta}\dfrac{1}{s}\left(\xi\sqrt{Var(\varepsilon)}N_2 - N_1\right) \\ t_{2s}{}^{M} - t_2^{O} = \dfrac{1}{1+\xi\sqrt{Var(\varepsilon)}}\dfrac{1}{1+\eta}\dfrac{1}{s}\left(\xi\sqrt{Var(\varepsilon)}N_2 - N_1\right) \end{cases}.$$

We can guarantee that our conjecture holds when $\xi\sqrt{Var(\varepsilon)} \ge \dfrac{N_1}{N_2}$. Finally, the bound for ξ is:

$$\frac{N_1}{N_2}\frac{1}{\sqrt{Var(\varepsilon)}} \le \xi \le \frac{\alpha-\beta}{\beta}\frac{1}{\sqrt{Var(\varepsilon)}},$$

which further requires

$$\frac{N_1}{N_2} \le \frac{\alpha-\beta}{\beta}.$$

Hence, given those conditions hold, we have analytically solved this specific multiplicative stochastic toll problem.

Lemma 6: The multiplicative stochasticity not only increases risk-averse commuters' travel costs, but also change their equilibrium departure behaviors.

Now, individual costs of Group 1 and Group 2 can be shown as follows:

$$\begin{cases} \overline{C}_1^{mul} = n\delta \dfrac{N_1+N_2}{s} \dfrac{1+2\xi\sqrt{Var(\varepsilon)}}{1+\xi\sqrt{Var(\varepsilon)}} \\ \overline{C}_2^{mul} = \delta \dfrac{N_1+N_2}{s} \dfrac{1+2\xi\sqrt{Var(\varepsilon)}}{1+\xi\sqrt{Var(\varepsilon)}} \end{cases}.$$

If we compare $\left(\overline{C}_1^{mul}, \overline{C}_2^{mul}\right)$ with $\left(\overline{C}_1, \overline{C}_2\right)$, it is obvious that no matter the commuters are risk-averse or not, Group 1 ends up worse off under the multiplicative stochasticity. Group 2 will be worse off if Group 2 commuters are risk-averse ($\xi > 0$). If both groups are risk-averse ($\xi > 0$), we have $\dfrac{1+2\xi\sqrt{Var(\varepsilon)}}{1+\xi\sqrt{Var(\varepsilon)}} > 1$ and thus it is easy to show that $\overline{C}_1^{mul} - \overline{C}_1 > \overline{C}_2^{mul} - \overline{C}_2$.

Corollary 4: If both groups are risk-averse, then commuters in both groups will have higher costs under the multiplicative stochastic toll than under the deterministic toll. Moreover, Group 1 suffers more from this stochasticity than Group 2.

One interesting observation is that with the multiplicative stochasticity, the equilibrium departure *sequence* of two groups switches when commuters are risk-averse. When commuters are risk-neutral or there is no multiplicative stochasticity, Group 1 will depart in the middle of the time horizon and Group 2 will depart at two ends. Moreover, the switch under the multiplicative stochasticity is the least desirable result of sociality: the group with a higher time value turns out to be wasting more time than the group with a lower time value. Some numerical examples (See Section 4.5) suggest that the total social costs are even higher than those in the case without any toll. Hence, this observation suggests that when commuters are risk-averse, providing a multiplicative stochastic toll (even if this stochastic toll is the socially optimal toll when commuter is risk neutral) will hurt the total social welfare.

Theorem 6: With multiplicative stochasticity, two groups of commuters can switch from their optimal departure sequences to which the total social welfare hurt the most.

4.4.2 With Congestion Derivatives

Similar to the previous section, we compare the central planner's decision to the market-based solution.

Suppose the central planner offers a forward contract for free. As $\overline{C}_i^{mul} - \overline{C}_i \geq 0$, it is obvious to conclude that the incentive compatible constraint is satisfied for each commuter and the ex post departure rate will be socially optimal.

However, if a forward contract has a time invaraint positive price (i.e., not free), then it is not possible to sustain the all-buying incentive compatible constraint and ex post optimal departure equilibrium simultaneously. The argument can be constructed as follows: suppose the ex post equilibrium is socially optimal and the contract cost is $K > 0$. Let's focus on the arbitrary commuter who departs at time t_s. As this arbitrary commuter faces a zero toll, the contract value for this arbitrary commuter will be zero. Hence, firstly, this arbitrary commuter will not purchase any positive priced contract ex ante – the incentive compatible constraint can not be satisfied for all commuters. Secondly, other commuters will have incentives to not purchase the contract as well. Specifically, at the ex ante when every commuter decides whether to purchase the contract, this arbitrary commuter will have an expected cost of $\bar{C}_i$ and all other Group *i* commuters will each has an expected cost of $\bar{C}_i + K > \bar{C}_i$. Then some commuters without purchasing the derivative will deviate from ex post optimal equilibrium to travel right before t_s without being queued. In this continuous time model, as this commuter travels close enough to t_s, his/her new cost will be smaller than $\bar{C}_i + K$. Hence, the ex post equlbrium will not be socially optimal. So, in order to maximize the total social welfare, the forward contract price must be equal to zero.

Lemma 7: With the multiplicative stochasticity and forward contract, only if the contract price is zero so that all commuters will have incentives to purchase the contract, then the departure sequence can be guided to its socially optimal sequence ex post. Moreover, both groups will be better off with the forward contract than without. Furthermore, Group 1 who are more risk-averse will benefit more from the forward contract than Group 2.

However, on the other hand, instead of a forward contract, if the central planner is able to propose a proportional tax on the toll, then we can eliminate the externalities due to multiplicative stochasticity. For instance, if the central planner charges tax at the rate $tax(t) = \dfrac{u(t) - u^*(t)}{u(t)}$ and redistributes the tax revenue back to commuters according to their departure times, then the negative effect of the multiplicative stochasticity can be contained compeletly and the departure behavior will be socially optimal as well.

Lemma 8: With multiplicative stochasticity and tax revenue redistribution, the departure sequence can be guided to its socially optimal sequence ex post.

If $E(\varepsilon)$ equals zero so that the no-arbitrage forward contract price is zero, then this market-based mechanism will be incentive compatible and every commuter will purchase one. Hence the ex post equilibrium will be socially optimal.

However, if $E(\varepsilon)$ is not equal to zero, for example $\varepsilon > 0$, then it is not possible to simultaneously guarantee both the incentive compatible constraint and ex post equilibrium to be socially optimal. The proof is identical to what we have done in the previous section. Hence, it is possible that the market-based mechanism can be beneficial to society, but it might not achieve the social optimum.

Lemma 9: With the multiplicative stochasticity and the market-based mechanism, it is possible to achieve social optimum in some but not all cases.

Hence, in sum, we have the following theorem:

Theorem 7: With the multiplicative stochasticity, the central planner can always use forward contract or taxation to achieve the social optimum. However, the market-based mechanism can be beneficial to the society, but may only achieve the social optimum at some specific cases.

4.5 Stochastic Bottleneck Model: Numerical Studies

In this section, we will study more general stochastic cases, where analytical results are either unmanageable or impossible. Similar to Ramadurai et al. (2007), we formulate this problem as a Mixed-Linear Complementarity Problem (MLCP). Firstly, we discretize the time interval $[0,T]$ into K subintervals with length of $\Delta = \frac{T-0}{K}$. Then under the equilibrium, the following equations need to be satisfied simultaneously:

Cost Function for Group 1: $C_1(i) = \begin{Bmatrix} \alpha_1 TT(i) + \beta_1 \max\left[0, t^* - (t + TT(i))\right] \\ +\gamma_1 \max\left[0, (t+TT(i)) - t^*\right] + E(u(i)) + \eta_1 \sqrt{Var(u(i))} \end{Bmatrix}$

Equilibrium Condition for Group 1: $r_1(i) * (C_1(i) - C_1^*) = 0$

Satisfy demand for Group 1: $\sum_{i \in \{1,\dots,K\}} r_1(i) = N_1$

non-negativity for Group 1: $\begin{cases} r_1(i) \geq 0 \\ C_1(i) \geq 0 \end{cases}$ for any $i \in \{1,2,3,\dots,K\}$

Cost Function for Group 2: $C_2(i) = \begin{Bmatrix} \alpha_2 TT(i) + \beta_2 \max\left[0, t^* - (t + TT(i))\right] \\ +\gamma_2 \max\left[0, (t+TT(i)) - t^*\right] + E(u(i)) + \eta_2 \sqrt{Var(u(i))} \end{Bmatrix}$

Equilibrium Condition for Group 2: $r_2(i) * (C_2(i) - C_2^*) = 0$

Satisfy demand for Group 2: $\sum_{i \in \{1,\dots,K\}} r_2(i) = N_2$

Non-negativity for Group 2: $\begin{cases} r_2(i) \geq 0 \\ C_2(i) \geq 0 \end{cases}$ for any $i \in \{1,2,3,\dots,K\}$

Travel Delay 1: $TT(1) = \max(0, \frac{r_1(1) + r_2(1)}{s} - 1)$

Travel Delay 2: $TT(t) = \max(0, TT(t-1) + \frac{r_1(t) + r_2(t) - s}{s})$ for $t > 1$

$TT(i) \geq 0$ for any $i \in \{1,2,3,\dots,K\}$

where $TT(i)$ is the total travel time of commuter departing at time *i*, and $r_j(i)$ is the departure rate at time *i* for Group *j*.

Among those equations, some conditions are worth further explanations. Equilibrium Condition means that if there is departure for group *j* at time *i*, $r_j(i) > 0$, then the group *j*'s commuter at time i will have his/her individual cost minimized and must equal to the equilibrium cost C_j^*. Travel Delay 1 and Travel Delay 2 define the travel time dynamics and ensure the positivity of the travel time. Intuitively, if there exists a solution to those equations simultaneously, then we will obtain the equilibrium departure rate, $r_j(t)$.

During numerical studies, a large range of parameters has been deployed to ensure the robustness of our results. In general, for each parameter combination, we first validate our code's accuracy by using the deterministic model, for which we have analytical results. Then, every additive stochasticity model and multiplicative stochasticity model are investigated under three cases: (1) with a toll; (2) with a toll and forward contracts; (3) with a toll and European call options. For all these cases, we tested two types of random stochastic processes: ε_i follows i.i.d. uniform distribution or Geometric Brownian Motion.

Even with powerful solvers, solving these equations still remains a very challenging task. Due to the nature of this problem, we need to balance between the accuracy and the computational time. With small time intervals and a large discrete size, we should gain more accuracy, but the computational time will be much longer. Furthermore, even with ample computational power, we still may fail to find an equilibrium with proper approximations, especially at the time t^*, at which not only the toll switches from increasing to decreasing but also the commuters' schedule delay cost parameters change. Hence, for some parameter combinations, different solvers may yield totally diverged solutions, and we need to adjust the discrete size and re-run the program to reconcile those differences. To this end, we coded this problem with GAMS and find that, in general, Lindoglobal can effectively solve these equations with a reasonable accuracy. Using dual 2.80GHz CPU and 2G RAM, each run may take from seconds to hours depending on the discrete size.

In spite of all numerical studies, we will only plot and present our results by one set of parameters. Despite the quantitative difference, all numerical experiments exhibit similar patterns, which will be elaborated in details later on. Hence, for the sake of space, one example should be sufficient enough for illustration. Specifically, we set $\alpha_1 = 2,\ \beta_1 = 1,\ \gamma_1 = 3,\ \xi_1 = 1,\ \alpha_2 = 4,\ \beta_2 = 1.2,\ \gamma_2 = 3.6,$ and $\xi_2 = 10$. In terms of stochasticity, we assume the random variables follow an i.i.d uniform distribution with mean 0 and variance 1, ($E(\varepsilon) = 0$, $\mathrm{var}(\varepsilon) = 1$), respectively. At last, we set the number of commuters in each group to be 50 ($N_1 = N_2 = 50$) and the capacity of bottleneck to be 3 ($s = 3$). Discretizing time into 100 intervals, we are able to solve these equations around 30 seconds.

Without stochasticity, if we impose the optimal toll, then the two groups' departures will be perfectly separated as shown in Figure 19. Specifically, at the equilibrium, Group 2 departs in the middle of the time horizon, while Group 1 departs at two ends. Furthermore, the total departure rate equals the bottleneck capacity, and there is no congestion at all. Comparing to the case where no toll was imposed, the total social cost decreases from 2205 to 1359.

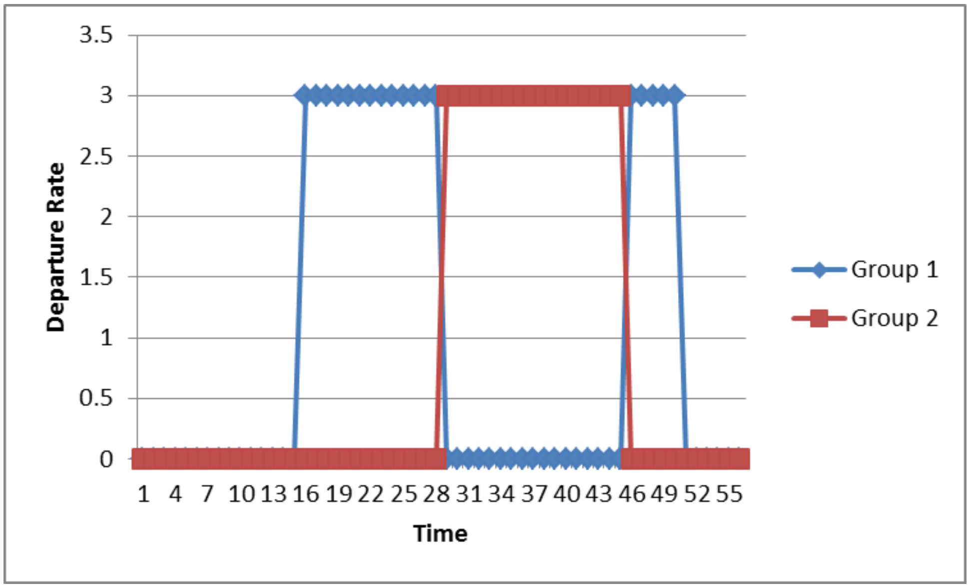


Figure 19. Departure rate without stochasticity

However, if we have the multiplicative stochasticity, even under the same expected optimal toll, we observe that two groups switch their departure sequences as shown in Figure 20. Consequently, four harmful effects from the stochasticity can be identified clearly. Firstly and most obviously, the stochasticity increases commuters' risk premiums. Secondly, this stochasticity changes commuters' departure behaviors to the worst-case scenario: the group with a high time value actually wastes more time by departing further away from the preferred arrival time than the group with a low time value. What's worse, the third impairment to our society is coming from the fact that there is little departure close to the preferred arrival time, because everyone prefers to avoid the high uncertainty in toll price around that time. At last, the fourth harmful factor is the congestion: even though the expected toll is optimal, the risk aversion nature of commuters will still force them to deviate from the socially optimal solution and queue before the bottleneck (See Figure 21).

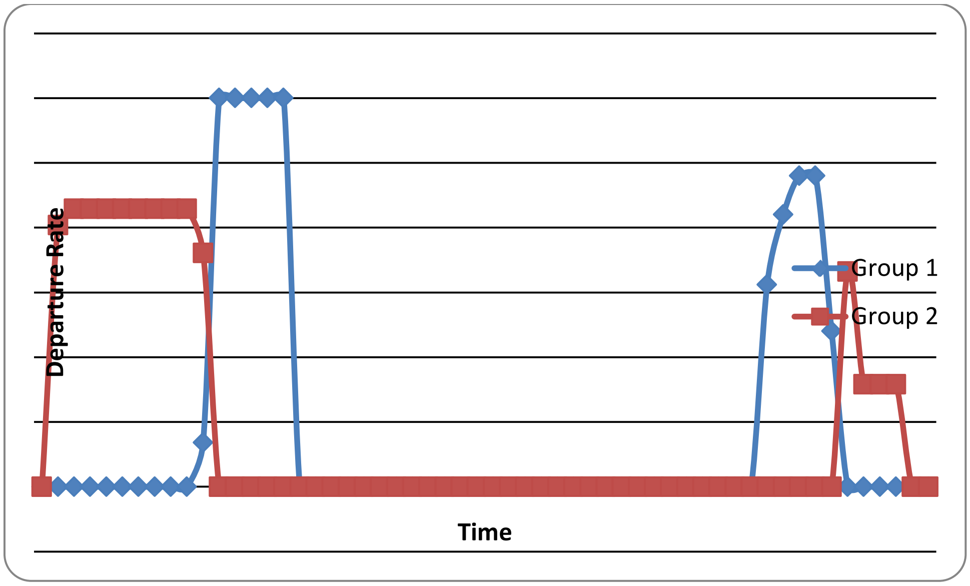


Figure 20. Departure rate with multiplicative stochasticity

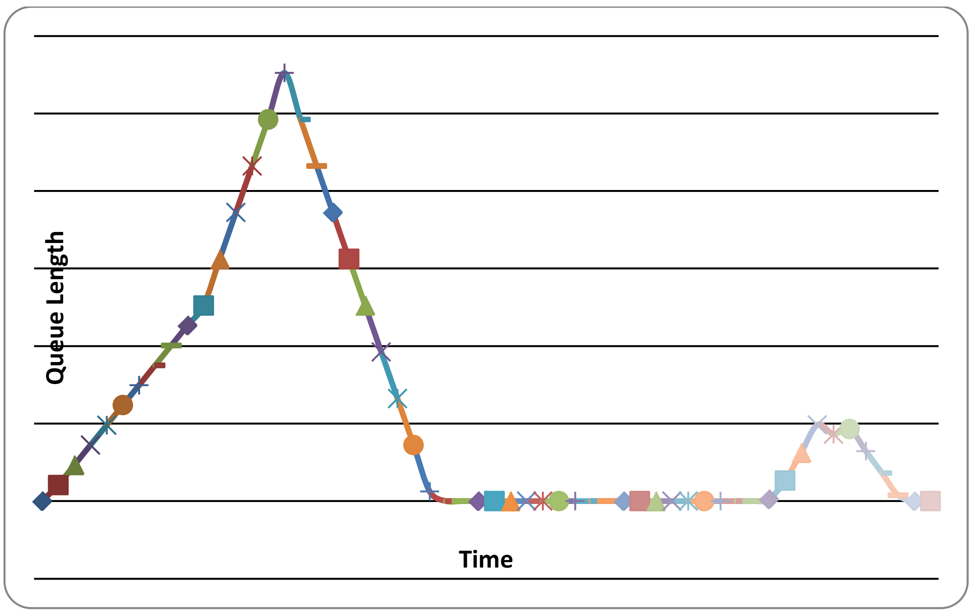


Figure 21. Total queue length with multiplicative stochasticity

Considering the total social cost, we are astonished by the devastating results. In the case where we do not have stochasticity or commuters are risk neural, the total social cost will be 1359 with an optimal toll. However, with a stochastic toll, this number will top 4020. More interestingly, if we calculate the actually total risk premium, which is the direct cost associated with the risk and can be calculated by $\sum_{i=0}^{100}\left(r_1(i)\xi_1 + r_2(i)\xi_2\right)\sqrt{Var(u(i))}$, then this cost is only 88. That means, because of risk aversion and stochasticity, the increase in the total social cost, excluding risk associated cost, will be 2573, which is even higher than the total social cost when there is no toll at all.

Now, if we use the forward contract, then we will get back to the identical result as the case without stochasticity and decrease the total social cost to 1359. Hence, we verify that the forward contract can actually be used to eliminate the influence of stochasticity.

On the other hand, assuming that forward contracts are not available, we need to consider other market-based mechanisms. In particular, we consider a market offering European call options, which allows the option holder to purchase an asset on this option's expiration date at a pre-specified price. We run this new numerical test and find out that we can still shrink the total social cost to 1894, a 53% decrease in the total social cost from the case where European call options are not used. The new departure rate and congestion level are illustrated in Figure 22 and Figure 23.

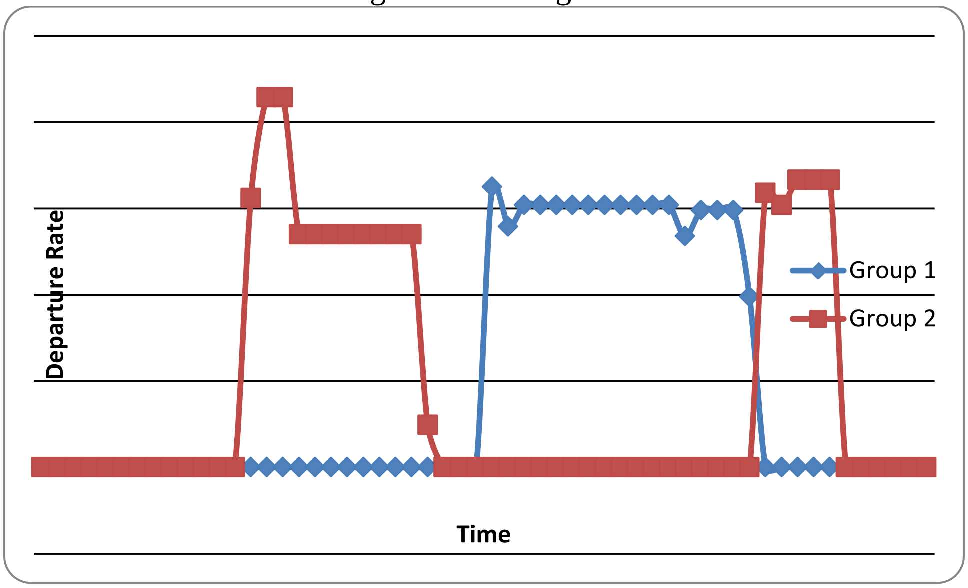


Figure 22. Departure rate after introducing European call options

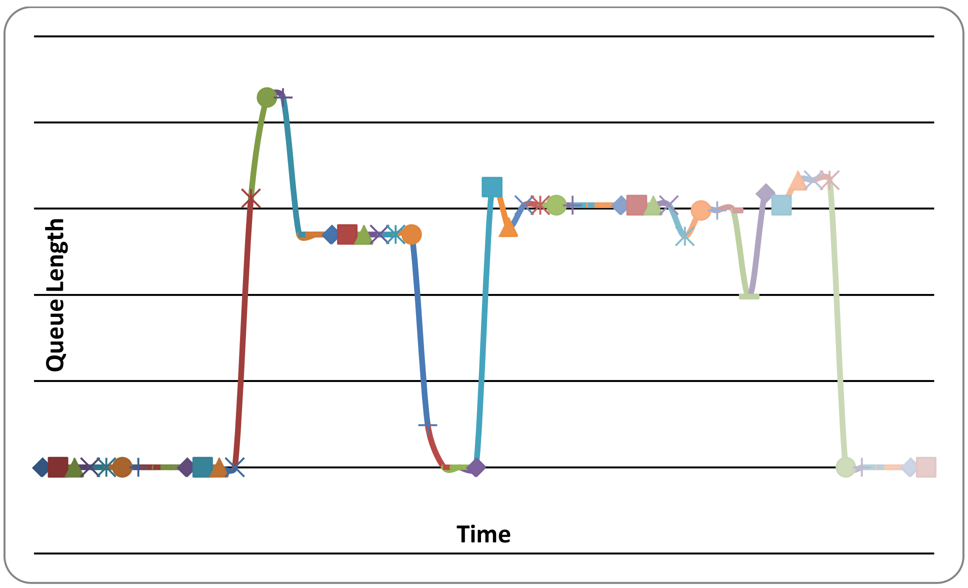


Figure 23. Queue Length after introducing European call options

4.6 Conclusion

In this study, we analyze the equilibrium departure behavior of heterogeneous risk-averse commuters facing a stochastic toll. In particular, we are able to derive the equilibrium departure behavior for the additive stochasticity. Although the general equilibrium departure behavior is extremely difficult and tedious for the multiplicative stochasticity, we are able to propose an iterative method to identify the equilibrium, and provide one example to analytically demonstrate the process of finding the equilibrium. Yet, successfully adopting this iterative method requires the researcher to find an appropriate initial conjecture. Otherwise, it will be very time consuming to verify varying conjectures and analytically identify an equilibrium. Hence, for more general types of stochasticity and congestion derivatives, we formulate this problem as a MLCP, which can be solved by commercial solver quite efficiently.

To gauge the effect of risk-aversion and the stochastic toll, we compare the equilibrium departure behavior under stochastic settings to their deterministic benchmarks. In particular, we find out that the stochasticity generates negative externalities in four ways: (1) it increases risk-averse commuters' risk premiums; (2) the multiplicative stochasticity forces risk-averse commuters to travel much earlier or later than the socially optimal time to avoid high uncertainty in thetoll price; (3) due to risk aversion, some commuters, who have a higher time value and should travel in the middle of the time horizon under a socially optimal scenario, end up traveling at the two ends and switching departure sequence with those commuters who have lower time value and should travel at the two ends under the socially optimal scenario; (4) the multiplicative stochasticity can generate congestions. Hence, with those externalities, it is not surprising that commuters will deviate from the socially optimal solution and increase the total social cost.

Finally, we show that congestion derivatives can be very effective in mitigating negative externalities and can even achieve socially optimal departure equilibrium with either a central planner or a market-based mechanism. Specifically, both the central planner and the market-based mechanism can be very effective both to eliminate all socially negative externalities and to reach the socially optimal solution with the additive stochasticity. However, with the multiplicative stochasticity, the central planer can always attain socially optimal solutions by subsiding or taxing, while the market-based mechanism can be beneficial to society but only achieves the socially optimal solution at some specific cases.

The natural extensions of our research include the followings: (a) generalize the types of stochasticity; (b) incorporate more sophisticated congestion derivatives such as the American call option; (c) expand the single bottleneck model to a general network; and (d) extend a bottleneck to a hydrodynamic traffic flow model.

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