

Development of a Freight Benefit/Cost Methodology for Project Planning

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**Development of a Freight Benefit /Cost Methodology
for Project Planning**

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Executive Summary

Project Overview

Future reauthorizations of the federal transportation bill will require a comprehensive and quantitative analysis of the freight benefits of proposed freight system projects. To prioritize public investments in freight systems and to insure consideration of the contribution of freight to the overall system performance, states and regions need an improved method to analyze freight benefits associated with proposed highway and truck intermodal improvements that would lead to enhanced trade and sustainable economic growth, improved safety and environmental quality, and goods delivery in Washington State.

This project develops a process to address this need by building on previous and ongoing research by some project team members with the goal of developing an agency-friendly, data-supported framework to prioritize public investments for freight systems in Washington and Oregon. The project integrates two ongoing WSDOT funded efforts: one to create methods to calculate the value of truck and truck-intermodal infrastructure projects and the other to collect truck probe data from commercial GPS devices to create a statewide Freight Performance Measures (FPM) program. This integration informs the development of a framework that allows public agencies to quantify freight investment benefits in specific areas such as major freight corridors and across borders.

Study Questions and Key Findings

Why are commuter and transit centric economic analyses and performance metrics insufficient to fully address freight systems?

- While the valuation of time for freight transportation is often conducted using the hourly wage of the truck driver, the driver's wage reveals only part of the true value of time in a freight operation. Freight transport typically involves at least shippers (customer) and a carriers (trucking firm). Thus, the value placed on a reduction in travel time differs considerably across shippers of different products based in part on the value of the product, as well as attributes like perishability. Other factors affecting the value of time include distances involved in point-to-point shipments, transport mode connectivity, logistic reorganization, as well as opportunity costs.
- Benefits and impacts extend beyond the roadway and the carriers on it. As carriers experience increased efficiencies on the roadway, shippers may adjust long run scale, scheduling, and logistics. The markets and industries involved similarly may witness changes to production patterns in distribution or supply regions. Increased efficiency may lead to economic development potential, creating a public benefit. Together, these benefits fit into the realms of distributive and generative effects.
- More than simply a consideration of time on the roadway, freight users experience a potentially greater benefit of infrastructure improvement through increased reliability of

the time necessary to traverse a roadway or route. In today's just-in-time marketplace, consistent and reliable time estimation directly impacts the bottom line of freight dependent industry.

How does this research address and incorporate freight benefits for use by Departments of Transportation?

- Identification of measurable freight benefits begin through discussion and partnership with three State Freight Plan Technical Teams. These teams were comprised of experts involved in the movement of freight throughout Washington's intermodal system, and identified by the Washington State Department of Transportation's Freight Systems Division. The three teams were Urban Goods Movement, asked to focus on jobs, the economy, goods delivery and clear air for all; Global Gateway, asked to focus on national and state import/export activities; and Rural Economy, asked to focus on farm-to-market and manufacturing goods movement. The teams were tasked with the identification of measurable benefits and potential data sources that are important to shippers, freight carriers, air quality stakeholders, labor, and federal, state, regional and local governments including ports. After consideration, the Technical Teams' list of prioritized benefits included:

- Improved travel times,
- Improved travel time reliability,
- Reduced truck operating cost,
- Safety improvement,
- Freight network connectivity improvement,
- Network resiliency improvement,
- Improved air quality: truck emissions,
- Economic output.

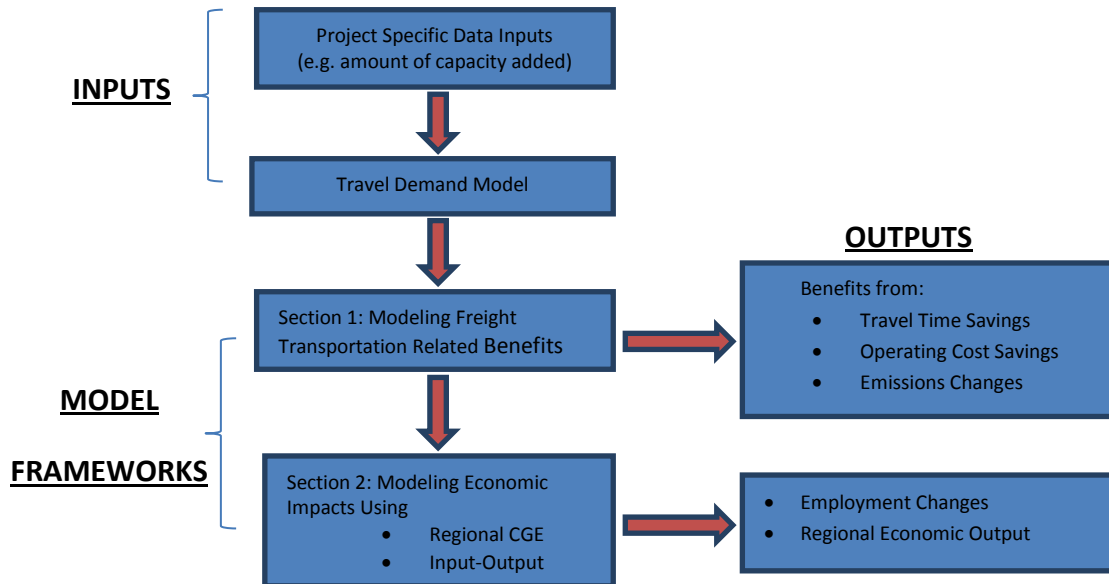
- Infrastructure improvement projects that reduce operating costs and travel time of freight users on the roadway is an activity that inherently affects the **productivity and economic efficiency** of the user; two critical components that are addressed in the National Freight Policy provisions of MAP-21.

- Using the model framework below, the capacity to step-wise proceed from the roadway

improvement specifics through to economic outputs in the form of both Benefit Cost analyses that may be incorporated into standard department analyses, as well as an additional consideration of the induced economic impacts resulting from the on-the-road benefits.

Benefits are identified as those social welfare affects that may, when incorporated into the larger prioritization process of WSDOT that includes already well-established passenger benefits, be compared to the costs of an investment over the analysis period. The subsequent ‘impacts’ are then the effects that the investment has on the economy and is measured by changes in economic output and employment.

FIGURE 1: Freight Project Impacts Analysis Workflow

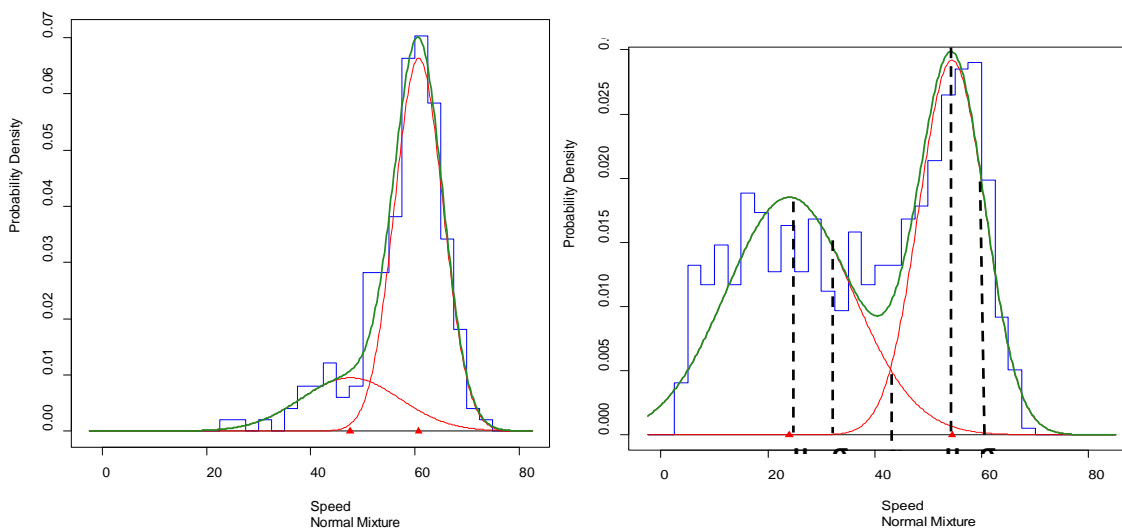


- Acknowledging the high value placed on reliability by freight system users, additional measures are developed to effectively inform prioritization processes. Several techniques are evaluated for their functionality with available data and to meet departmental needs.

- **Travel Time Standard Deviation:** the standard deviation is a measure of the spread of observed time taken to traverse the specified distance. The larger the value of the standard deviation, the lower travel time reliability. In other words, as the standard deviation increases, the ability to reliably gauge the length of time a trip will take decreases.

- **Percentiles:** a numerical difference between the average travel time and a predictable (upper) deviation from the average. This difference (a real number) is then directly used to monetize the value of unreliability.
- **Bimodal Method:** Instead of examining the travel time distribution, this technique plots the spot speed on each segment during given time periods, and assesses the reliability by evaluating the speed distributions with the assumption that the travel time is unreliable if bimodal distributions are observed, and otherwise (unimodal distribution) it is reliable.

FIGURE 2: Example Travel speed distributions during a reliably fast (left pane) and an unreliable (right pane) period



What are the recommended take-home messages from this project?

- As shown in Figure 1, the benefit estimation and subsequent economic impact analysis depend on the availability and effective implementation of a travel demand model (TDM). While the use of a TDM presents a dramatic improvement

over the status-quo, there are some significant limitations to using these models in a freight benefit-cost analysis.

- Some TDMs do not have sufficient modeling capability to be used for freight project benefits analysis.
 - May be manifested in either modal capability or in modeler capacity.
 - Freight demand in household and employment-based TDM is fixed.
 - Model results are a function of user defined parameters.
 - Truck speed is deterministic.
-
- Where economically possible, available, and measurable, all manifested benefits to the freight system should be incorporated into the models. This includes regionally specific data, safety improvement, and travel time reliability.
 - Benefit Cost Analyses such as those developed in this project and those widely used by transportation agencies, provide a necessary first step in understanding whether society is better off under a proposed investment, than where the investment is not made. However, a standalone BCA falls short in allowing an agency to consider the resultant increases in productivity and economic efficiency from an infrastructure investment. These productivity considerations are becoming a routine necessity under new federal transportation bills (e.g. MAP-21).

- Industry responses to the increased transportation efficiencies may include such reactions as job creation, wage level changes, business activity, and tax base expansion resulting from increased accessibility and connectivity. These responses are captured via an Economic Impact Analysis (EIA) that enables the enumeration of the likely change in the economy as a result of the benefits identified previously.
- We identify and compare two models of analysis of economic impacts: (1) Input-Output (I-O) Model, and (2) Computable General Equilibrium (CGE) Model.
- Where infrastructure projects are large enough and productivity is increased to the point that now fewer trucks – and therefore fewer drivers – can meet the demand needs, we may experience a reduction in employment in the transport-by-truck sector. The I-O model does not pick this up. However, the CGE is able to directly model increased productivity of an industry and are thus able to model the entire economy-wide reaction to the infrastructure improvement that is a result of decreased operating cost and travel time.
- It is for this specific ability to model productivity changes that a regional CGE model should be incorporated into the prioritization process as an aside to the BCA.

- The selection of proper reliability measures for benefit-cost analysis project includes the evaluation of data availability and the estimation of post-project freight reliability.
- If sufficient travel time data is available, e.g. every 5 minute loop detector data, we recommend using the buffer time which represents the extra travel time travelers must add to ensure on-time arrival to measure the travel time reliability. When data is sparse, e.g. low reading frequency GPS data, we suggest using the bimodal approach employed by WSDOT to evaluate the travel time reliability as this method does not require extensive travel time data, but still can examine and classify the reliability based on spot speed data.

CHAPTER I

Introduction and Background

As the austere conditions of many state governments continue, state Departments of Transportation (DOTs) are increasingly asked to economically justify their budget requests (Babcock and Leatherman, 2011). For trade heavy states like Washington, the movement of freight becomes a considerable component of an economic justification. To prioritize public investments in freight systems and to insure consideration of the contribution of freight to the overall system performance, states and regions need an improved method to analyze freight benefits associated with proposed highway and truck intermodal improvements that would lead to enhanced trade and sustainable economic growth, improved safety and environmental quality, and goods delivery in the Northwest.

The established evaluation criteria of any transportation project largely influences the project selection and direction, thus for freight to become an integrated component of a managing agency's transportation program, it must be recognized and acknowledged through the project evaluation criteria (NCHRP, 2007). Before implementing any freight project evaluation criteria, an agency must first be able to identify the performance measures that matter to the freight industry and freight-related systems. At this time there is no known nationally-accepted framework for analyzing the full-range of freight-related impacts stemming from transportation infrastructure projects. Complex interactions with separate, but not isolated, effects among economic, environmental, and social components with sometimes conflicting priorities make freight impacts often more difficult to measure than those of other highway users (Belella, 2005).

Despite the complex nature of the development of a tool to prioritize public investment in freight systems, it is an endeavor that has become increasingly important to satisfy. Over the last two decades pressure on agency officials from the public, executive administrations, and congress, as well as improved management systems for transportation infrastructure and movement have all lead to increasing need for performance measures and management (Cambridge, 2009). The freight provisions included in MAP-21 make this ever more necessary. Under MAP-21, national freight policy goals include economic competitiveness, reduced congestion, increased economic productivity and economic efficiency, as well as safety, security and resilience (§1115; 23 USC 167). Additional freight provisions require the USDOT to encourage the development of a comprehensive plan for immediate and long-range freight planning and assessment by each state (§1118) (MAP-21, Significant Freight Provisions. <http://www.fhwa.dot.gov/map21/freight.cfm>).

To successfully compete in a new funding world with significantly reduced monies for transportation infrastructure, states must become even more pragmatic about the means by which they emphasize and prioritize investments. Identification of the necessity to include freight performance measures in local, state, and national transportation plans, and rise above anecdotal understandings of system performance, is becoming evident as more municipalities and state agencies move towards implementing freight related plans (Harrison et al., 2006; MnDOT, 2008). Having said that, current project prioritization methodologies used by many DOTs often do not specifically include freight benefits of projects and they have not taken advantage of new data made available by GPS

technology (instead they depend on modeled data). In an era where performance data are increasingly available it makes sense to integrate this data into the developing project prioritization process to the extent possible.

This project addresses this need by building on previous and ongoing research of project team members with the goal of developing an agency-friendly, data-supported framework to prioritize public investments for freight systems in the region. The project strategically integrates two Washington State Department of Transportation (WSDOT) funded efforts: one to create methods to calculate the value of truck and truck-intermodal infrastructure projects, and the other to collect truck probe data from commercial GPS devices to create a statewide Freight Performance Measures (FPM) program. This integration provides a framework that allows public agencies to quantify freight investment benefits in specific areas such as major freight corridors and across borders.

This report lays out the supporting literature in a review of the state of practice concerning the relevant evaluation of transportation infrastructure investments as it pertains to travel time and travel time reliability. This literature and a collaborative effort to engage the freight community laid the groundwork for the development of the first phase of this project; a truck freight prioritization framework. The developed methodology is then tested on a pair of case studies, with the intention of incorporating a freight specific determination of the economic value of project benefits in addition to the economic impacts as captured by either an Input-Output (I-O) model or a regional computable general equilibrium (CGE) framework. The second phase of the project

establishes a methodology to estimate travel time and travel time reliability from GPS data, followed by an investigation of the methods that can be used to estimate future truck travel time.

Literature Review

State of the Practice

Performance measures are designed to be a quantifiable aide in the identification of how well a project can meet a defined set of goals and as a tool to communicate justifications for decisions to the public (Harrison et al., 2006). The execution of these measures within economic analyses for highway projects allows the identification of projects optimizing benefits to the public through cost-effective design and construction and returns on the public investment, as well as the ability to target scarce resources to their best use. Several strands of economic analysis strategies are often available for use in highway planning, including Life-Cycle Cost Analysis (LCCA), Benefit-Cost Analysis, Risk Analysis, and Economic Impact Analysis (FHWA, 2003). Which is employed, often depends on the goal of the analyses, and the user or policy makers' interest in the magnitude of transport's potential impact on economic growth.

The most common approach to the economic analysis of benefits generated to freight systems in a policy realm is a microeconomic consideration in which an analyst calculates the benefits as direct cost savings and travel time reductions, in addition to indirect impacts of said time and cost reductions stemming from logistical reorganization (Weisbrod, 2008). This is the approach characterized by the majority of benefit cost

analyses (e.g. FHWA, 2003; Lakshmanan, 2011). In 2010, the American Association of State Highway and Transportation Officials (AASHTO) released an updated resource for the benefit-cost analysis of highway projects (AASHTO, 2010). Known as *The Redbook*, the manual recognizes user benefit analyses in transportation planning as a fundamentally economic process, as opposed to simply that of an engineering issue. The manual identifies the need to use traffic performance data, including: traffic volume, speed, travel time, and other data related to the segments under project consideration. These data are needed for both the current status of the segment, as well as the expected data under any project alternative. Further, the manual breaks down the development of user cost factors based on values of time for various vehicle classes (auto, transit bus, and truck categories, each with various categories of trip purpose and means to value the occupants' time), occupancy rates of those vehicles, as well as their operating costs (fuel, oil, maintenance, tires, insurance, license, and registration) and accident rate cost parameters. These cost factors are then related to the obtained traffic performance data in order to determine user costs. Despite the enormity of considerations available in toolkits like *The Redbook*, they generally lack full consideration of regional economic impacts extending beyond the direct benefits of an improvement, particularly when it relates to the freight system and its needs, such as reliability, buffer indices, logistics, and just-in-time standards. These omissions readily provide an impetus for more freight inclusive BCA methods and to a greater degree, an economic impact framework. Let us begin with a consideration of the justification for the incorporation of freight specific needs into an analysis framework.

Incorporating Freight

To date, most analyses of the impact of highway infrastructure improvements on state transportation system performance have focused on the impact on passenger traffic or the total vehicle count. However, there are important differences between passenger and freight transportation that need to be considered to accurately assess the impact of highway infrastructure improvements. This is particularly true when it comes to the consideration of such improvements on congestion and travel time reliability and determining the appropriate dollar value to use for changes in reliability for freight. It quickly becomes apparent that the matter is much more complicated than for passenger travel.

For passenger travel, the total value of a trip is calculated as the value to the driver and any passengers on board. The value to these occupants of the change in reliability is generally accepted to be their value of time multiplied by the change in transit time. While there is still a debate in the literature regarding the appropriate value of time to use (i.e. is it the average hourly wage rate in the area---or should it be half of that for transit time, etc.), and whether the relationship between a reduction in reliability and social value is linear, it is clear that these issues pertain to the driver and occupants of the vehicle and thus are directly related to the operation of the vehicle.

Some have interpreted the valuation of time for freight transportation in a parallel fashion by using the hourly wage of the truck driver. However, the driver's wage reveals only part of the true value of time in a freight operation. Freight transport typically involves a

shipper and a carrier (trucking firm). The value placed on a reduction in travel time differs considerably across shippers of different products, distances involved in point-to-point shipments, transport mode, etc.

Alstadt and Weisbrod (2008) mention several specific reasons why the valuation of freight transportation travel-time savings has been underestimated in the past:

1. Costs to carriers of transportation extend beyond the driver's wages, for example, wages of dock workers and other support costs.
2. Because shipments have an opportunity cost, benefits to the shipping firms from freight time reduction are not considered.
3. Logistical reorganization for shippers such as the reduction in warehousing costs due to faster and more reliable networks is ignored.

For freight to become an integrated component of a managing agency's transportation program, it must be recognized and acknowledged through the project evaluation criteria (NCHRP, 2007). This recognition and subsequent suitable accounting of increasing domestic freight tonnage becomes a paramount issue as tonnage is predicted to increase by 57 percent between 2000 and 2020. In the 2010 State of the Union Address, President Obama announced a *National Export Initiative* with a goal set to double exports by 2014. Should this prediction or the Administration's goals be met, or even in the ballpark, the resultant growth will approach and likely exceed capacity in many regions, contributing to congestion throughout the surface transportation system and decreasing the reliability of not only freight shipment times (Cambridge, 2006), but also travel time and reliability

of all system users, producing direct impacts on attractiveness and competitiveness of U.S. businesses, ports, and states. Weisbrod et al. (2001) identified congestion effects as mitigating factors of the benefits achieved through agglomeration in urban areas and further identify firms who are heavily dependent on trucks to be the most negatively impacted by congestion. *NCHRP Report 570* (2007) suggests that the most effective mechanism for ensuring freight considerations are part of the process is to modify and enhance existing processes aimed at ranking improvement processes. Their generalized categories of consideration for freight inclusion are:

- **Safety and Security**
- **Mobility and system performance**
- **Economic development and land use**
- **Growth management**
- **Intermodal and multi-modalism**
- **Environmental impact**
- **Quality of life**

Similarly, Belella (2005) identified seven freight measure categories:

- **Reliability** – A measure of delivery performance,
- **Responsiveness** – A measure of origin to destination speed,
- **Flexibility** – A measure of the agility of a system to respond to market changes that maintain or improve competitive advantages,
- **Costs** – A measure of the cost of moving freight,
- **Asset Management** – A measure of an organization’s effectiveness in managing assets to support demand satisfaction,
- **Safety** – A measure of achieving a safe condition through danger, risk and injury reduction,
- **Security** – A measure of the ability to mitigate security risks and threats,

Meeting the needs of the freight community through freight specific projects or the consideration of freight needs in overall transportation activities may only be accomplished if the mechanism by which the freight community benefits from transportation improvements is thoroughly understood. Shippers make their choice of transport mode based on a combination of service price and also service quality (of which travel time and reliability are but one component.) Travel time reliability is one of the most significant factors to freight system users. The US DOT Office of Operation noted that “Shippers and freight carriers require predictable travel times to remain competitive.” (USDOT, 2006a). A survey conducted by the FHWA found that reliability is the measure that meaningful to both public and private sectors, and it influences the logistics strategies of manufacturers, distributors, retailers, and freight system operators. Thus reliability was selected as one of the two freight performance measures by FHWA. Another measure is travel speed (Jones and Sedor, 2006). The willingness of freight shippers to pay for faster and more reliable service depends on many factors. Whether the shipper or receiver of the commodity being shipped is using a just-in-time inventory (JIT) system also makes a difference in the value of the service to the shipper. Variability in transportation reliability could impact supplies for the production process and end up forcing shippers to carry more costly inventories to guard against potential supply chain disruptions.

In this light, performance measures and project evaluation must be viewed from both system and user perspectives. In other words, measures should reflect how users and their customers experience the system (Hendren and Meyers, 2006). *NCHRP Report 570*

(2007) identifies an approach to defining and promoting existing transportation projects that may best address freight needs:

- Review the freight needs and deficiency statement.
- Identify potential projects based on existing bottlenecks.
- Conduct outreach to private stakeholders to validate potential projects.
- Refine and select key freight project concepts.
- Define preliminary project descriptions.
- Review detailed project descriptions with private partners.
- Integrate final project list into overall transportation program activities.

Though the above cited report is intended as a guidebook for small and medium sized metropolitan areas, the list above can begin the process of consideration at a state or regional level as well, as it sets the stage for agency personnel responsible for freight to begin the identification process of including freight needs in the overall transportation plan (ibid).

Identifying Benefit Distribution

While estimates of project costs have been relatively straight forward, the same cannot be said for benefits, particularly those of higher orders (Cambridge, 2006). Considerations for the reason behind the lack of accurate and comprehensive benefit measures generally stem from difficulties in their evaluation. Freight projects, particularly those of large scale tend to have economic development impacts that require consideration of public

and private benefits, often with a national or at least regional level significance. As markets and industries grow in national and international scale, so too does freight shipping distances. Increased international trade typically follows suit and places ever larger demands on major international gateways, whether air, sea or border crossing by truck and rail. These facilities are nearly always serviced in some capacity by truck freight. As usage of these facilities grows, the necessity to accurately depict the benefits that flow from increased efficiencies within the system becomes a vital consideration in transportation project evaluation. Demands for increased efficiency within the transportation system stem not only out of the growth in national and international goods movement, but also efforts to broaden regional market areas and out of necessity to respond to increased efficiencies in the production and logistic processes involved in supply chain management and industries that have largely transitioned to just-in-time scheduling, (ibid). As communication and logistic efficiencies have increased, increased pressure on manufacturers in terms of responsiveness has been applied by consumers and serviced industries alike (EDRG, 2008).

The role of freight movement in a region is strongly tied to its relationship to its ‘core’ and ‘traded’ industries. With several major west coast ports, the Northwest’s economy is tightly bound to these traded industries, where we understand traded industries to be those industries that produce and sell more goods than what can be consumed locally, and thus are selling products to a national or international market and provide a flow of incoming dollars to the local economies (EDRG, 2008). Since the development of the interstate highway system, manufacturing industries have become interdependent upon

the trucking industry (ibid). The degree to which an industry is dependent upon this system varies considerably. In their evaluation of Portland's traded industry use of transportation, the Economic Development Research Group identified the agricultural industry (NAICS 111) as relying upon Truck usage for 73 percent of their transportation needs, while publishing industries (NAICS 511) are 35 percent reliant upon Truck and 36 percent on postal.

There is little continuing argument that investments made in transportation infrastructure and facilities provides both economic and non-economic benefits to areas both proximate and more distant to the investment. The Federal Highway Administration (FHWA) identifies these benefits in the form of distributive effects and generative effects (FHWA, 2001a):

- **Distributive Effects** - Those leading to redistributions of income, population and employment; these effects do not necessarily result in a net output gain.
- **Generative Effects** - Those realized by increased efficiency in resource usage.

The Freight Beneficiaries

Significantly different from traditional transportation economic analyses that focus their primary emphasis on passenger, and transit benefits, freight oriented projects should be able to explicitly account for the chain of manufacturing, logistic, and distribution processes involved in freight movement (Cambridge, 2006). Halse and Ramjerdi (2012) conclude that some methods used previously for valuing passenger transportation,

particularly collecting data from stated preference surveys, can be applied to freight transportation, but caution that the freight industry is heterogeneous so care must be taken to survey and represent each segment. Beyond simply commodity differences influencing value, they find that shipping firms and freight carriers often have different opinions regarding the value of travel time and reliability. In their 2006 *Guide to Quantifying the Economic Impacts of Federal Investments in Large-Scale Freight Transportation Projects*, Cambridge Systematics identifies five elements of a typical chain and the manner in which a transportation project may impact them:

- **Carriers** – Benefits are directly impacted by travel time, reliability, and accessibility as well as safety.
- **Shippers** – Where competition typically occurs among freight carriers, both within and between modes, the variation in benefits to the carriers may be passed onto their shipper customers. Increased efficiencies experienced by the carriers is directly relatable to the shippers ability to configure long run changes to their scale, scheduling and overall logistics.
- **Industries and Markets** – On the other end of the carrier’s performance are the freight recipients, thus gained efficiency by the carrier may result in changes to market production patterns as well as distribution and supply regions.
- **Non-Freight Impacts: Economic Development** – As business productivity (shipper, carrier, and recipient) is enabled, changes to activity patterns impacting job creation are enhanced, thus creating a public benefit.
- **Other Public Impacts** – Economic development impacts in turn can affect demand for various public and private facilities. These impacts subsequently

may have environmental impacts as changes in economic activity affect energy resources and emissions.

The Federal Highway Administration takes a slightly different approach to categorizing the chain and order of benefits. The FHWA (2001a, b, c) creates a scheme based on the order of benefits:

- **First-Order Benefits** – Immediate cost reductions to carriers and shippers, including gains to shipper from reduced travel times and increased reliability
- **Second-Order Benefits** – Reorganization-effect gains from improvements in logistics. Quantity of firms' outputs changes; quality of output does not change.
- **Third-Order Benefits** – Gains from additional reorganization effects such as improved products, new products, or some other change.
- **Other Effects** – Effects that are not considered as benefits according to the strict rules of BCA, but still may be of considerable interest to policy makers. These could include, among other things, increases in regional employment or increases in rate of growth of regional income.

With transportation infrastructure that is largely built out, the national highway system (NHS), many infrastructure construction operations result in marginal improvements in how users experience the network. Direct users of the transportation system tend to experience the network in terms of the average amount of time they are required to spend on it from their origin to destination, as well as the variability in that time. Both travel

time and reliability affect user mobility and accessibility. Here, we understand mobility to be the ability to travel, and accessibility as the ability to reach desired destinations and activities. These travel time and reliability considerations are additionally impacted by safety considerations of the network (Cambridge, 2009).

Travel Time and Reliability

Development of the various metrics drawn from the literature and discussed throughout this report stem from consideration of travel time and reliability, as it is relatable back to various costs like: labor, fuel usage, and emissions, to name but a few. Travel time measures are of the nature that makes their improvement easily relatable to both policy makers and system users (NCHRP, 2008). However, despite its easy to understand metrics, several managing entities have found travel time to be an incomplete metric, and cumbersome to utilize in a comparative manner, especially as a means of comparison between proposed projects in corridors of different length. Additionally, the utilization of travel time in a BCA framework necessarily requires the conversion of time into a monetary metric through an assumption of the value of time of the operator of a vehicle.

This valuation in relationship to freight however, does not capture the complete impact time variation has on goods movement. The types and value of the commodities being moved (e.g. perishables) will affect the time sensitivity of the shippers and thus the time value placed on fast and reliable transit (Alstadt and Weisbrod, 2008). As straight forward as the assignment of the value of time to an operator may appear, differences in shippers' preferences and/or the commodity being shipped produce significant variability

in its empirical measurement. Shippers of differing commodities, as often identified through surveys place different values on time and time reliability, thus their responses to travel time changes, positive or negative, may produce starkly different results (Taylor, 2011). Appropriate scaling of the value of time in a commodity specific framework is of particular importance when examining the impacts of reliability changes on freight dependent industries (Weisbrod, 2008).

While consideration of travel time is certainly a performance measure of concern for freight movement, its ability to be further nuanced into an assessment of highway reliability is a particularly important continuation of the benefit deliberation for freight oriented projects, especially for those carriers and shippers with time sensitive shipments. As time sensitivity increases, the minimization of the time-in-route distribution should be as narrow as possible (Allen et al., 1994). For these shippers, and other users of the highway system, avoidable time spent stuck or delayed on the road is a nonproductive activity for which there is an opportunity cost (Cohen and Southworth, 1999). Time sensitivity often plays out in the form of necessity to meet overnight delivery guarantees or to meet departure of the next component of the supply chain (i.e. meeting the departure of a rail car, flight or barge movement), thus Belella (2005) suggests the incorporation of performance measures that can be related to the percentage of ‘cut-offs’ met or the percentage of appointments fulfilled.

Reliability may be defined in terms of the variability of travel time. Large variability in travel time has several important economic impacts. First, carriers must account for

variability by planning for some additional mean delay above what could be expected over the free-flow travel time. Second, freight system customers have a window of on-time performance allowed for intermodal connections. To measure reliability, models typically estimate cumulative incident related delays as a function of volume-to-capacity ratios (Cambridge, 2006). In this sense, it is not necessarily the recurrent delay that heavily impacts reliability, as these are easier to account for by carriers and shippers. As such, the two types of delay (incident and recurrent) are valued differently; the ITS Deployment Analysis System (IDAS) used by the Federal Highway Administration values non-recurrent delay at three times the value of recurrent (Cambridge, 2006). When it comes to day-to-day variation in travel time, several early studies indicate that vehicle incidents such as accidents and breakdowns are the major cause. This includes not only major accidents, but also lesser incidents like “fender-benders” and breakdowns (FHWA, 2005; from Cohen and Southworth: Lindley, 1987; Giuliano, 1988, Schrank et al., 1993).

As state departments of transportation, metropolitan planning organizations, and other transportation planners turn to performance based measures to procure and maintain public and federal assistance in response to growing pressures of accountability, they almost unanimously recognize the value placed on sensitivity of system users to delay and unreliable conditions (NCHRP, 2008). This has become particularly evident with commercial users, though is certainly present for both passenger and freight travel (Cambridge, 2009). Harrison et al. (2006) suggest that the evolution of a largely just-in-time delivery system that now comprises much of freight movement, has increased the

need for reliability measures over simple travel time performance. Industries involved in just-in-time delivery can reasonably account for expected delays; it is the variability that substantially alters delivery timing estimates. Low system reliability, or predictability, in itself has costs associated with it, as it affects productivity (NCHRP, 2008).

Substantial effort has been spent to develop travel time reliability measures relying upon statistical techniques. The two common approaches, mean versus variance and percentile of travel time, are discussed in the following paragraphs. This discussion is followed by a third approach that incorporates measures based on GPS data.

1. Mean versus Variance

The first approach uses the mean, or average, travel time as well as the standard deviation of travel times. This method is straight forward and relies upon an extensive dataset collected from a variety of sensors and automatic vehicle location devices (e.g. loop detectors, radar detectors, and GPS devices). The standard deviation is a measure of the spread of travel time observations. The larger the size of the standard deviation from the mean, the lower travel time reliability.

One example of the mean-variance approach is the research on measuring the crossing-border travel time and travel time reliability for freight led by USDOT (USDOT, 2010). This research evaluated the capability of truck GPS data in measuring crossing-border truck travel time. The study location was Otay Mesa International Border between the US and Mexico. GPS data was provided by a third-party provider and monthly crossing-

border truck trips between January 2009 and February 2010 were between 2,000 and 9,000. According to the statistics, the truck trips retrieved from GPS data fell between 3 to 5 percent of the actual total crossing border truck trips, which was recognized as confident sample size for travel time reliability measurement by the research team. Individual truck crossing border travel time was retrieved from GPS data, and was used to estimate the average and variance of travel time by time of day and month of year. A large standard deviation from the mean was observed, ranging from 61 to 81 percent of the mean value. From finding the study concluded that carriers crossing the border experienced very low travel time reliability.

Similarly, the California Department of Transportation led the development of the web-based Performance Measurement System (PeMS) to clean the raw data collected from over 30,000 loop detectors every 30 seconds in California and compute the performance measures (CADOT, 2012). Aggregated average vehicle travel time and standard deviation were calculated from loop data every five minutes. The standard deviation was viewed as an indicator of travel time reliability and was used to explore the factors associated with unreliability (Chen et al., 2003). It was found that the travel time variance after incidents was much larger than the value in normal situations, which shows that incidents are one of the factors leading to unreliable travel time.

2. *Percentiles*

Unreliability is also commonly measured as a relationship to the 95th percentile travel time, or the buffer time which is defined as the 95th percentile of the travel time

distribution minus the mean time. Different researchers may use the 80th or 85th or other percentiles as the base. The *percentiles* approach is presented as a numerical difference between the average travel time and a predictable (upper) deviation from the average. This difference (a real number) is then directly used to monetize the value of unreliability. The FHWA proposed a series of travel time reliability measures based on the travel time distribution. The measures include 95th percentile travel times, a planning time index, and the buffer index, (USDOT, 2006).

95th Percentile Travel Time and Planning Time Index

The 95th percent travel time method is used to measure how bad the traffic would be based on observations over certain time period (e.g. one year). In another words, it estimates the time travelers need to plan for, in order to accomplish their trips on time. It is recommend by the National Cooperative Highway Research Program (NCHRP) as the simplest indicator of travel time reliability (NCHRP-618, 2008). One application is the web-based “Best Time to Leave” system implemented by WSDOT (<http://www.wsdot.com/traffic/seattle/traveltimes/reliability/>). This system estimates the best time to leave in order to arrive at the destination on time based on historical observations. For instance, the 95th percent travel time for a trip from Auburn to Renton is 22 minutes and therefore 95th percent of the time the travelers need to leave at 7:38 to ensure on-time arrival at 8:00 am.

The Strategic Highway Research Program 2 (SHRP2) proposed travel time reliability monitoring system (TTRMS) to measure travel time reliability under various conditions

and identify the factors of unreliability (SHRP2, 2012). The TTRMS consists of data collection, processing and reliability calculation, and unreliability analysis procedures. The travel time reliability measures proposed in SHRP2 are similar to the 95th percent travel time method, which mainly relies upon the distributions of travel time observations. The distribution is presented in three ways: the first is a histogram with y axis represent the frequency and x axis represents the travel time; the second way is to represent the distribution of travel time via a probability density function (PDF); and the third way in which the distribution is presented in a cumulative density function (CDF). The distributions under different conditions, e.g. no event, incident and weather reflect the travel time reliability. For instance, San Diego region developed the region travel time monitoring system, which is part of the California PeMS system, based on a mix of loop detectors and radar detectors located on freeway and arterial. The system analyzed travel time PDF under each congestion condition.

While single loop and dual loop detectors are the most common data sources for travel time distribution and reliability calculation due to the availability of dataset obtained from the detectors, the usage of GPS data for travel time reliability assessment has gained increasing attention given the growing market penetration rate of GPS technology.

FHWA and The American Transportation Research Institute (ATRI) have been collecting truck GPS data on freight system performance since 2002 (USDOT, 2006b). The GPS data was used to evaluate travel time and travel time reliability along freight important corridors, and identify freight traffic bottlenecks. Similarly, Figliozzi et al, (2011) studied travel time reliability along multi-segment trucking freight corridors using commercial

GPS data obtained from ATRI along the I-5 corridor in Oregon. They used the 95 percent travel time method to quantify travel time reliability and estimate the additional freight vehicle cost per mile due to unreliable travel time.

Buffer Time and Buffer Time Index

Buffer time is defined as the extra travel time travelers must add to the average travel time to allow for on-time arrival, and it is calculated as the difference between the 95% travel time and average travel time (USDOT, 2006a). The buffer time index is calculated by dividing buffer time by the average travel time.

Federal and regional transportation agencies have used buffer time and the buffer time index to evaluate system performance. The FHWA and ATRI have evaluated how information retrieved from GPS device could provide data to support freight travel time reliability measures. The buffer index measure was employed to evaluate freight travel time reliability along five major freight corridors in the U.S. (USDOT, 2006b). The Minnesota DOT evaluated freight performance along I-94/I-90 from the Twin Cities to Chicago using archived truck GPS data and freight travel time reliability was evaluated using the buffer time index (Liao, 2009). The major limitation of buffer time index is that it may underestimate the unreliability when travel time distribution is right-skewed. To ensure reliable measure, the median-based buffer index is recommended instead of the averaged-based buffer index (Pu, 2011).

Planning Time and Planning Time Index

Planning time is the travel time needed to plan to ensure on-time arrival, and is equal to the 95th percentile travel time. The planning time index represents the total travel time a traveler should plan for to ensure on-time arrival 95% of the time relative to the free flow travel time and it is computed as the 95th percentile of travel time divided by free-flow travel time.

While the buffer time index estimates how much extra travel time to add for allowing uncertainty in travel time, the planning time index estimates the total travel time that should be planned. It is calculated by comparing the near-worst travel time (95th percentile travel time) to free flow travel time. Therefore the planning time index differs from the buffer time index in that it considers both recurrent delay and unexpected delay (NCHRP, 2008). Although there are differences between the two measures, the buffer time index and the planning time index show same trend along a roadway (Lyman and Bertini, 2008).

3. *Measures Relying Upon GPS Data*

The measures discussed in the above sections rely upon considerable observations collected from loop detectors or truck GPS data. Two of the major challenges of using GPS data in performance measures are the low number of observations in areas with low truck traffic volume, and low GPS reading frequency (Harrison and Schofield, 2007). It is challenging to evaluate reliability when the data set is sparse using the methods discussed above, and therefore most existing highway performance measure systems depend upon

the traffic data collected from loop detectors, which represents the general traffic, rather than freight specific traffic. However, loop detectors are not available for all study areas, and data retrieved from loop detectors may underestimate the freight delay, a result found by comparing estimates based on loop detector data with truck GPS data (Figliozi, 2012). Thus, recently emerging research focuses on using GPS data from trucking industry and commercial vehicles for freight performance measures. The FHWA cooperated with ATRI to make the truck GPS data available to several universities to support freight performance measure evaluation with truck GPS data. The Highway Performance Monitoring System (HPMS) highlighted in the Moving Ahead for Progress in 21st Century (MAP-21) also requires new data sources and innovative technologies to support efficient and reliable freight performance measures. Meanwhile, many transportation research agencies are seeking methods and measures to evaluate truck freight travel time reliability with truck GPS data.

Figliozi et al., (2011) proposed an algorithm to evaluate travel time reliability along I-5 corridor through the state of Oregon based upon truck GPS data accessed from ATRI. A process was designed to ensure sufficient GPS reads for travel time reliability analysis based on the minimum sample size, which was determined by segment length, time period, density of counts and required accuracy. If the sample size along a segment was smaller than the minimum sample size, either the time period length was increased or moved to the next segment.

WSDOT has evaluated the truck reliability performance and identified freight bottlenecks using GPS sample data collected since 2008 (WSDOT, 2011; Zhao et al., 2013). The data represents approximately 3 percent of total trucks traveling in Washington State. The probe data is sparse on most segments, and are not sufficient to provide a daily travel time distribution to support travel time reliability analyses using the methods discussed in the previous sections. Instead of examining the travel time distribution, the WSDOT plots the spot speed on each segment during certain time periods, and assesses the reliability by evaluating the speed distributions with the assumption that the travel time is unreliable if bimodal distributions are observed, and otherwise (unimodal distribution) it is reliable. It was found that a mixture of two Gaussian distributions provided the best fit for the truck speed observations. The probability density function of a mixture of two Gaussian distribution is shown in Equation 1-1. The parameters are fitted based on the maximum likelihood rule.

$$f(x) = \alpha \cdot n(x, \mu_1, \sigma_1) + (1 - \alpha) \cdot n(x, \mu_2, \sigma_2)$$

$$n(x, \mu_i, \sigma_i) = \frac{1}{\sqrt{2\pi\sigma_i^2}} \cdot \exp\left[-\frac{(x - \mu_i)^2}{2\sigma_i^2}\right]$$

Equation (1-1)

The approach defines the travel condition as unreliable if and only if

$|\mu_1 - \mu_2| \geq |\sigma_1 + \sigma_2|$, $\alpha \geq 0.2$, and $\mu_1 \leq 0.75$, otherwise, it is viewed as reliable. For the reliable performance, it is subdivide into reliably fast and reliably slow depending on the average speed. Truck reliability serves as one indicator for ranking freight bottlenecks in Washington State. The major advantage of this methodology is that the reliability

evaluation does not require extensive daily observations of travel time, but only spot speed, which is relatively easier to obtain.

A study evaluated the trip travel time reliability beginning in the Boerum Hill neighborhood of Brooklyn and ending at JFK airport using probe GPS data (SHRP2, 2012). The challenge of evaluating travel time along the route is that few probe vehicles travel the entire route from beginning to end. Thus the total route travel time was constructed by evaluating individual links. The Monte-Carlo simulation method was employed to simulate the travel time based on the assumption that consecutive links have strong linear dependence. The research demonstrates the feasibility of evaluating trip reliability with limited probe data.

Issues in Valuing Freight Travel Time and Reliability

Despite the relative ease of communicating benefits in manners understood by policy makers and the travelling public, the use of travel time, delay, and reliability as a performance measures is hindered by the necessity for substantial, accurate, and complex data, with few entities having the processes in place to suitably incorporate them into the planning process. Those that do have the means to fully incorporate these measures, do so but on a limited number of corridors within the state (NCHRP, 2008). Even where entities are able to characterize many of the state corridors, most of the existing work on congestion and reliability measurements focus on monitoring and reporting based on historical trends and existing values, and not on the means by which improvements to the system may be measured (ibid).

While it is likely that no single value may capture the breadth of travelers' concern regarding congestion, the literature does suggest four components whose interaction does capture a substantial diversity of concerns. These four components or measures are duration, extent, intensity, and variation. Lomax et al. (1997) described the measures as:

- **Duration** – Length of time for which congestion affects a system, or the fraction of the day in which speed indicates congestion
- **Extent** – A quantification of the number of people/users affected by the congestion. Typically measurable by person-miles or person trips travelled during congestion. Geographic extent of the congestion is also considered here by measuring the route or lane miles affected.
- **Intensity** – Measures the perceived severity of the congestion. Generally conceived of as a difference between the desired condition and the condition of congested.
- **Reliability** – This component describes the variability in the first three and consists of two components: recurring delay, daily delay from high volume that is predictable, and; the more difficult to predict, incident delay (Lomax et al., 1997; NCHRP, 2008). WSDOT has similarly defined recurring congestion as that congestion that is relatively predictable and caused by routine traffic volumes operating in a typical environment, while non-recurring congestion is defined as unexpected congestion caused by unpredictable events such as accidents (Bremmer et al., 2004).

The NCHRP 398 report (Lomax et al., 1997) and follow-up NCHRP Report 618 (NCHRP, 2008) suggest a series of potential mobility and reliability measures. The suggested measures are: (1) Delay per Traveler; (2) Travel Time; (3) Travel Time Index; (4) Buffer Index (BI); (5) Planning Time Index; (6) Total Delay; (7) Congested Travel; (8) Percent of Congested Travel; (9) Congested Roadway; and (10) Accessibility. They further break these measures into two types: Individual measures (1-5); and Area Measure (6-10). Here, Individual measures are characterized as being those that best relate to the individual traveler, whereas the area measures are applied to the corridor or region level. Considering there are ten different measures here, not all are feasible or relevant for every potential project and care should be taken to utilize the right measure for the analysis area or goal (NCHRP, 2008). For example, when considering a multimodal analysis, they recommend using measures 3-6 and 10; whereas, for analysis areas consisting of a short road section, measures 1, 2, 4, and 5 are most appropriate.

Once a measure of reliability is determined, there still remains the difficult issue of placing a value on time for freight and also on time reliability. As will be illustrated below, these may involve quite different values. A related measure often referred to in studies is *the Reliability Ratio*, defined as the ratio of the value of freight travel time reliability (VOFTTR) to the value of freight travel time (VOFTT) savings¹. If this ratio is greater than one, the respondent values reliability more highly than travel time, and if it is below one, the respondent values travel time more highly than reliability. As discussed

¹ Transportation Research Board. "Transportation Benefit-Cost Analysis, Travel Time Reliability." Accessed August 28, 2012. <http://bca.transportationeconomics.org/benefits/travel-time-reliability>.

below, this may be due to differences in shippers' preferences and/or the commodity being shipped. One way to obtain values of time is to directly survey shippers. As will be seen below, shippers of different commodities may have vastly different ideas of the value of time and time reliability, thus requiring survey of shippers of all types of commodities on a corridor to get a weighted average value to use in a B-C analysis. Most empirical studies have used either stated preference (SP) or revealed preference (RP) surveys and techniques after administering the appropriate survey to a sample of firms. A SP study provides respondents hypothetical scenarios with two or three response options, and from these decisions can statistically measure values of time and reliability. In a RP transportation study, values of time and reliability are calculated from the costs that a shipper or carrier has incurred in past or current transactions and the prices these companies charge customers. In both types of studies, survey design is critical as well as the selection of an appropriate sample.

Surveys that directly ask respondents the value of a change in standard deviation tend to be unsuccessful in finding accurate values for reliability. Part of this problem is due to the inability for individuals to assign value in terms of standard deviation. Halse and Killi (2011) demonstrated through an experiment that a well-designed iterative SP survey analyzed econometrically or statistically, can provide a statistically significant value to the change in the standard deviation of travel, even if individual drivers and managers do not consciously apply the concept. Weisbrod (2008) discusses the use of powerful regional modeling tools such as IMPLAN and REMI for forecasting the economic benefits of transportation infrastructure improvements. His report puts forward

guidelines for choosing between these predictive models, especially when travel time reliability is a planning consideration.

Allen et al. (1994) recommend using a *logistical cost savings* (LCS) approach in order to more fully capture the benefits to freight transportation from infrastructure improvements. This approach incorporates decreased warehousing costs, decreased costs through reduced travel time, decreased damage to shipped goods and vehicles from smoother and better paved roads, and more into the B-C metric. The authors mention two significant differences between the LCS approach and a tradition B-C analysis:

1. LCS factors in savings to carriers, shippers and customers from reduced truck accidents, in the form of reduced safety stock.
2. The authors argue that LCS more fully accounts for changes in average travel time as well as changes in travel time variability.

The USDOT (2006) also recommends a more holistic logistical cost approach to incorporate the change in costs beyond carriers to shippers and other transportation system users. This report poses two options to solve this chronic underestimation of benefits from infrastructure improvements:

1. For a less data-intensive option, the costs to carriers can be multiplied by an additional, 15% to simulate the costs of other system users.
2. Use shipper surveys to ask firms what their expected cost-reductions will be given a future infrastructure scenario or to ask general infrastructure use questions (such as modal dependence and transportation substitution possibilities) to extrapolate benefits for individual industries.

The Value of Freight Travel Time (VOFTT) and Value of Freight Travel Time Reliability (VOFTTR)

This section discusses some of the VOFTT and VOFTTR that have been used in past studies and also the results of studies that have sought to use analytical techniques to obtain these values either through RP or SP or a combination of techniques.

The Southern California Association of Governments (SCAG) (2005) used the Buffer Time Index in its 2005 report to calculate current costs and future cost-relief from congestion. In the same report, a value, considered a “very conservative estimate” of \$73 per truckload per hour was used as the VOFTT. The VOFTTR used was essentially a travel time multiplier. Depending on the time of day and resulting congestion, the VOFTT per truckload was multiplied by an additional 50% to 250%.

In some cases, such as the Highway Economic Requirements System (HERS) methodology (<http://www.fhwa.dot.gov/infrastructure/asstmgmt/hersindex.cfm>), monetary values for freight travel time are assigned in a way analogous to that for

passenger travel time value---by the value of time to the driver. This is a relatively easy way to get a monetary value as it simply requires a calculation using driver wages in an area; however, it misses much of the value that should be considered for freight. When the value of reliability is considered, then logistical considerations come into play and there are values attached with being early --- or being late (Halse et al., 2010)

All freight studies surveyed by De Jong et al. (2004) and Weisbrod et al. (2001) used either revealed preference (RP) (Wilson et al. (1986) studying US shippers), stated preference (SP) (Accent and Hague Consulting Group (2005) studying freight movement in the UK and Bruzelius (2001) studying Swedish shippers) or combined techniques (RAND Europe et al. 2004) studying shippers and carriers in the Netherlands) to generate regionally distinct VOFTT and VOFTR. As the measure of unreliability, most freight-specific studies used a definition such as the probability of not arriving at the specified time or time interval. Note that this differs from passenger studies that looked at the probability of delay.

The Values of Freight Travel Time (VOFTT) and Freight Travel Time Reliability (VOFTR) have been estimated in past studies in a variety of settings for a number of different countries. A summary of values obtained, the country for which the estimate applies, and the methodology used, are shown in Tables 1-1 and 1-2. Note that the monetary values presented in these tables are in terms of 2010 United States dollars (\$USD). If a published value was in terms of 2010 \$USD, no adjustment was necessary. If the values were in terms of \$USD of a year other than 2010, the CPI with base year

2010 was used to translate the values into 2010 \$USD. If the published values were in terms of a currency other than \$USD the foreign currency was first converted into \$USD using the average exchange rate for the year and then the CPI was used to convert the values into 2010 \$USD.

The Highway Economic Requirements System (HERS) technical report (Value of Time (VOFTT) estimation has two components: on and off the clock trips. For on the clock trips, the considerations are: wages, fringe benefits, vehicle costs and inventory carrying costs of cargo.

Zamparini and Reggiani (2007) find that measures of freight travel time savings are not consistent across modes, country or geography region. This reflects the fact that the contents of any given truckload of freight may not be homogeneous across regions or modes and some regions may concentrate on the transport of lower value than goods than others. Thus it is important to know the area's freight commodity mix to determine the value of time to use in the B-C study.

Zamparini, Layaa and Dullaert (2011) utilize a SP survey of 24 Tanzanian companies from a variety of industries. The firms were asked to report how often their outgoing shipments arrived on time as a measure of reliability. Of the 24 firms surveyed, 17 ranked reliability as more important than total travel time and 12 firms ranked reliability as more important than price of transport services, in terms of US dollars per ton/km. On average, companies in the sample gave lower values to reliability than they did to the

value of the transport time. Goods carried higher values of both increased reliability and travel time. They found for exported goods, the value of increased reliability was found to be \$0.00409/ton km and for internally transported goods, the value was \$0.00138/ ton km. By comparison, the value of decreased travel time was \$0.12302/ton km for exported goods and \$0.03891/ton km for internally transported goods. This suggests a reliability ratio of less than one. It also suggests that the value of time and the value of reliability may differ for the same commodity and shipper, depending on whether the shipment was destined for export or for domestic destinations. While this may be more important for a country such as Tanzania where the export sector may make a larger proportion of GDP than for the U.S., it is still something to consider for a region such as the Pacific Northwest where a greater number of shipments of some products (such as wheat) may be destined for export than for internal consumption.

In terms of the value of reliability, the magnitude has been shown to vary significantly with values as low as USD \$8.93/ transport hour (Tilahun and Levinson, 2010) to as high as USD \$233.31/ transport hour (Halse and Killi, 2011). Small and Verhoef (2007) find the reliability ratio for freight to be between .8 and 1.3, however we find a much greater range for the reliability ratio: between .033 and 8.68.

De Jong et al. (2004a) use SP and RP techniques and find that a 10% change in reliability as defined by percent of shipments not delivered on time is equivalent to:

\$1.38 per truckload for low valued raw materials and semi-finished goods

\$1.79 per truckload for high valued raw materials and semi-finished goods

\$3.66 per truckload for final goods with loss of value

\$3.44 per truckload for final products with no loss of value

\$3.90 per truckload for containers

\$2.42 per truckload for total freight transport by road

To provide an idea of the importance of distinguishing between the VOFTT and the VOFTTR, we calculate the Reliability Ratio as defined above for the studies we found that included both measures. These results are reported in Table 1-3. Note that in all cases the dollar values presented in the tables have been converted 2010 \$USD. This makes comparison easier but also illustrates the fact that there are vast differences in the values obtained from different studies, techniques, geographic areas, and commodities.

In most cases freight carriers value freight travel time reliability higher than freight travel time as reflected by the Reliability Ratio exceeding one. In the U.S. Weisbrod et al. (2001) find that shippers of manufactured goods have a Reliability Ratio of almost nine, the result for agricultural shippers is almost seven. Although shippers of mining products place a higher value on reliability than travel time but there is not as much of a difference (a Reliability Ratio of only 2.5).

These results make sense as shippers of manufactured commodities are often shipping products using JIT inventory systems and these are after high valued commodities.

Agricultural shippers are often dealing with perishable commodities. This illustrates the importance of using separate values for VOFTT and VOFTTR.

As Alstadt and Weisbrod (2008) succinctly address, travel-time savings have often been previously undervalued. Not only should an analysis consider travel-time in and of itself, but also for its impact on reliability. From these considerations, additional, compacting effects also stem. These stemming effects include issues pertaining to wages and support costs on either side of a transit (e.g. wages of dock workers or warehouse employees), opportunity costs to shippers, logistical reorganization throughout the entire chain as inventory holding costs shift and/or dwell times shrink. As the productivity of the trucks on the road increases, time and money put into the transport of a good may now be applied to a better use, thus rippling the increased productivity through the economy.

Economic Impacts

Highway congestion often acts as a mitigating factor of the achievable benefits of agglomeration in urban areas, particularly in relation to firms who are heavily dependent on truck transportation (Weisbrod et al., 2001). Further, recent industry surveys in Washington suggest 60 to 80 percent of elevated costs experienced by freight dependent industries' related to increased congestion may be passed on to consumers (Taylor, 2011). Findings such as Taylor's imply as these businesses are required to spend more to disburse their goods, that consumers will ultimately pay higher prices. Taking this notion in reverse, Allen et al. (1994) highlight that given the trucking industry's rather competitive nature, it may be assumed that much of any cost reduction resulting from an infrastructure improvement will be passed onto the shippers. These effects are subsequently felt throughout the regional economy.

While it is often speculated or assumed, that investments in transportation infrastructure contribute to economic growth and increased productivity (FHWA, 2004), the actual measurement of such a response resulting from a specific investment in a component of the system is often difficult to establish (Peters et al., 2008), and its full implementation is thus often underdeveloped or overlooked entirely. The benefits stemming from a transportation investment largely flow from the role of transportation infrastructure in providing a means of activity movement and interchange between locations (Weisbrod, 2007). Improvements via investments in transportation infrastructure that seek to minimize the barriers to travel have an effect of shrinking space and time (Lakshmanan, 2011). Subsequently, carrying an analysis forward only at the level of the BCA, may prove insufficient by not establishing the expanded ‘network’ effects felt by freight dependent and other service based sectors that rely on the services obtained on the transportation network. Peters et al. (2008) suggest that the individual parts of a transportation system may not capture its true economic value, and as such, the best measure may be one of the overall network quality. Additionally, Munnell (1990) found that a state’s investment in public capital has a significant impact on the state’s private employment growth. Thus in an approach identifying and accounting for economic impacts beyond the direct benefits, analysts may more fully capture the produced externalities of the infrastructure investments not captured by the BCA (Munnell, 1990; Nadiri and Mamuneas 1996, 1998; NCHRP, 1998; FHWA, 2004). It is in this type of approach that transportation benefits are transferred to economic impacts via labor, market, business and trade development, as well as increases in Gross Domestic Product

(GDP) or Gross Regional Product (GRP), and other organizational changes (FHWA, 2003; Lakshmanan and Anderson, 2002; Lakshmanan, 2011) and logistic reorganization (FHWA, 2004). The mechanisms by which transportation infrastructure investments enable economic development are multifaceted and include route development that enables new trade, improvement in travel cost and time, reduced uncertainty and risk, development of economies of scale in production and distribution and increased productivity from improved access to inputs and markets (Weisbrod, 2007). While the utility of such macroeconomic work rides on its ability to understand the larger effects, one should readily recognize its inability to identify the mechanisms by which the investments lead to benefits and thus wider impacts; thus the utility of BCA in uncovering the mechanisms, though potentially underestimating the larger effects (FHWA, 2004), is an important first step.

The need for a regional economic framework originates from the function freight transportation serves in the economy. Freight movement enables trade networks between industries and their market locations. Improvement to the routes reduces travel cost and thus production costs of goods, as well as reducing uncertainties and risk that come with unreliable delivery. These combine to increase industrial productivity (Weisbrod, 2007). Increases to the efficiency of a freight network then produce positive effects felt via job creation and economic activity (Allen et al., 1994; FHWA, 2001a, 2001b, 2001c; Weisbrod, 2007).

Regional economic and macroeconomic models have been developed to implement various functional interactions, like production and cost functions, to estimate relationships between infrastructure investment and productivity and long-term economic activity (NCHRP, 1998). At the macro level, infrastructure investment is viewed as a direct injection to the economy that can be inserted as an additional factor of production alongside private capital and labor (FHWA, 2004). Nadiri and Mamuneas (1996, 1998) measured the contribution of capital investment in highways to private productivity, finding that indeed it does contribute to growth and productivity at the industry and even national levels. Highway capital investments saw its largest impacts during the 1950s and 60s at a point when capital was in short supply and the interstate system was under development. Though the impact has since diminished, it still remains positive. Generally speaking, broad agreement exists to suggest that transportation infrastructure investments positively contribute to the overall economy; however, the magnitude of that contribution remains debatable (FHWA, 2004). In a 1990 work, Munnell found that public sector investment does produce a statistically significant impact on private sector output. Additionally, she found that a state's investment in public capital has a significant impact on the state's private employment growth (Munnell, 1990). These potential impacts readily provide an impetus for more freight inclusive benefit evaluation methods and to a greater degree, a regional economic framework that captures impacts to labor, markets, business and trade development, as well as increases in Gross Domestic Product (GDP) or Gross Regional Product (GRP), and other organizational changes (Lakschmanan and Anderson, 2002; FHWA, 2003; Peters et al., 2008; Lakschmanan, 2011).

In this light, regional transportation agencies and several state departments of transportation have sought economic frameworks to capture the economic impacts in addition to the transportation performance benefits. The Port of Portland readily identified that not all transportation bottlenecks and delays are equal when it comes to their economic impacts to the region and its traded industries (EDRG, 2008). They have employed a three-step process to identify the types of projects that are economically significant. The steps include site specific evaluations considering connectivity to key industrial sectors, vehicle usage characteristics like origin and destination, then finally, the magnitude of produced effects as they relate to travel time and predictability of travel time, size of same-day delivery markets, cost competitiveness of shipping rates, and access restrictions on trucks.

The Ohio DOT implemented a criteria and scoring methodology developed as a mixed strategy that uses a monetized BCA, which is then incorporated into a more qualitative scoring process. The scoring process is 55 percent transportation factors, 25 percent community and economic growth and development factors, and 20 percent derived from project sponsor investment factors. The transportation factors are broken into road, transit and freight columns such that the scoring criteria can be equally applied across modes. This scoring recognizes the economic reliance of the state on freight movement while also acknowledging the deleterious effects on quality of life for some urban areas as a result of noise, vibration, and pollution. The scoring system also allows for the influence of the logistics industry on economic development and thus the impact that balancing freight across modes can have on road congestion. Freight projects that will

increase capacity, as measured in TEU's, through a facility also have the potential to garner more points (ODOT, 2011).

Kansas and North Carolina Departments of Transportation developed highway project prioritization tools to assess the highway projects' economic impacts using the TREDIS economic modeling platform. The economic impact measures are direct and indirect employment, gross state product, personal income and productivity (Kansas DOT, 2010; North Carolina DOT, 2011). Michigan DOT also developed methods to explore the economic effects of transportation investments on personal income, employment, business sales and gross state product using the REMI economic model platform (FHWA, 2002). Similarly, Indiana DOT evaluated the statewide long range transportation plan by predicting the employees attracted from other states based on the improved market accessibility due to highway projects (Kaliski et al., 2000). This job creation was used as input to a REMI based model to estimate the full economic impacts including real personal income, gross state product, and output. Montana DOT (MDT) sought similar evaluative abilities in their development of their Highway Economic Analysis Tool (HEAT) based also on the REMI model. HEAT allows MDT to take travel performance metrics like travel time savings and ultimately relate them to commodity flows and subsequent benefit cost analyses (Cambridge, 2005). Though many consider regional economic models like REMI and TREDIS to be state-of-the-art, given their proprietary (commercial) nature, and the lack of complete transparency regarding their inner workings, some state agencies are hesitant to implement the models.

This brief literature review indicates that although the full benefits from transportation investments have been considered to be important, there is a need for a freight specific framework that considers both the direct transportation related benefits, and regional economic impacts using transparent economic models. The sections propose a transparent, freight specific methodology that relates the performance of the freight network as achieved through gains in efficiency and productivity and developed through regional transportation demand models and benefit cost analyses to the regional economy through a regional Input-Output and CGE model frameworks.

TABLE 1-1: Value of Freight Travel Time (VOFTT) (2010 \$USD)

Source	Survey Date	Criteria (Industry/Region)	Value
Fowkes et al., 2001*	1999	shippers, carriers, UK	\$95.4/transport hour
Halse and Killi, 2011		Shippers buying transport services	Value of Freight Travel Time Savings (VFTTS): \$9.65/ transport hour ; value of average transport time (VATT): \$16.81/ transport hour
Halse and Killi, 2011		Own-Freight Account	VFTTS \$54.04/hr per transport; VATT \$61.55/ transport hour
Halse and Killi, 2011		Transport Companies	VFTTS \$73.85/ transport hour; VATT \$72.35/ transport hour
Transek, 1990***		Sweden	\$3.26 VFTTS/ transport hour
Bergkvist, 2000***	1991	Sweden	\$2.08 VFTTS/ transport hour
Transek, 1992***		Sweden	\$4.35 VFTTS/ transport hour
Bergkvist and Johansson, 1997***		Sweden	\$6.53 VFTTS/ transport hour
Kurri et al., 2000***		Finland	\$9.86 VFTTS/ transport hour
Bickel et al., 2005***	2002	Finland	\$21.71 VFTTS/ transport hour
de Jong et al., 1995***		Denmark	\$45.09 VFTTS/ transport hour
Bickel et al., 2005***		Denmark	\$25.93 VFTTS/ transport hour
Waters et al., 1995***		Norway/Sweden	\$17.20 VFTTS/ transport hour
de Jong et al., 1995***		UK	\$7.66 VFTTS/ transport hour
Bickel et al., 2005***	2002	UK	\$13.54 VFTTS/ transport hour
Bickel et al., 2005***	2002	Ireland	\$20.70 VFTTS/ transport hour
NEA, 1991***		Netherlands	\$33.97 VFTTS/ transport hour
de Jong et al., 1995***		Netherlands	\$56.71 VFTTS/ transport hour
de Jong et al., 1992***		Netherlands	\$50.56 VFTTS/ transport hour
de Jong et al., 1992***		Netherlands	\$34.99 VFTTS/ transport hour
Gwilliam, 1997***	1995	Netherlands	\$57.12 VFTTS/ transport hour
de Jong, 2000***		Netherlands	\$24.36 VFTTS/ transport hour
Bickel et al., 2005***	2002	Netherlands	\$31.96 VFTTS/ transport hour
de Jong et al., 1995***		France	\$46.45 VFTTS/ transport hour
Massiani, 2003***		France	\$33.43 VFTTS/ transport hour

TABLE 1-1: Value of Freight Travel Time (VOFTT) (2010 \$USD) (continued)

Source	Survey Date	Criteria (Industry/Region)	Value
Bickel et al., 2005***	2002	France	\$31.51 VFTTS/ transport hour
Bickel et al., 2005***	2002	Austria	\$29.00 VFTTS/ transport hour
Bickel et al., 2005***	2002	Belgium	\$35.49 VFTTS/ transport hour
Bickel et al., 2005***	2002	Germany	\$25.93 VFTTS/ transport hour
Fehmarn Belt Traffic Consortium, 1990***		Denmark/Germany	\$28.69 VFTTS/ transport hour
Bickel et al., 2005***	2002	Switzerland	\$52.55 VFTTS/ transport hour
Bickel et al., 2005***	2002	Malta	\$8.64 VFTTS/ transport hour
Bickel et al., 2005***	2002	Portugal	\$9.67 VFTTS/ transport hour
Bickel et al., 2005***	2002	Spain	\$33.32 VFTTS/ transport hour
Bolis and Maggi, 2001***		Switzerland/Italy	\$19.72 VFTTS/ transport hour
Bickel et al., 2005***	2002	Czech Republic	\$7.73 VFTTS/ transport hour
Bickel et al., 2005***	2002	Hungary	\$19.23 VFTTS/ transport hour
Bickel et al., 2005***	2002	Lithuania	\$12.62 VFTTS/ transport hour
Bickel et al., 2005***	2002	Slovak Republic	\$10.91 VFTTS/ transport hour
Waters et al., 1995***		USA	\$17.06 VFTTS/ transport hour
Waters et al., 1995***		USA	\$10.95 VFTTS/ transport hour
Haning and McFarland, 1963***		USA	\$26.70 VFTTS/ transport hour
Kawamura, 2000***		USA	\$34.30 VFTTS/ transport hour
Wilbur Smith Associates, 2000***		USA/Canada	\$33.54 VFTTS/ transport hour
Waters et al., 1995***		Canada	\$21.56 VFTTS/ transport hour
Zamparini, Layaa, Dullaert, 2011		Tanzania, own freight account	\$0.0393 per ton-km
Zamparini, Layaa, Dullaert, 2011		Tanzania, carriers	\$0.1243 per ton-km
de Jong, et al., 2004a		Netherlands, low value commodities	\$50.92/ transport hour
de Jong, et al., 2004a		Netherlands, high value commodities	\$65.66/ transport hour

*Values calculated from table 1 in De Jong (2004a); ***Values calculated from Table 1 in Zamparini and Reggiani (2007)

All surveys Collected Via Stated Preference (SP).

TABLE 1-2: Value of Freight Travel Time Reliability (VOFTTR) (2010 \$USD)

Source	Survey Date	Criteria (Industry/Region)	Collection Method	Value
Weisbrod, Vary, Treyz, 2001	2001	Agriculture	SP	\$8.61/min ² (\$176.07/ transport hour)
Weisbrod, Vary, Treyz, 2001		Mining		\$1.02/min (\$60.60/ transport hour)
Weisbrod, Vary, Treyz, 2001		Manufacturing		\$13.78/min ² (\$222.73/ transport hour)
Accent and Hague Consulting Group, 2005*	1995	United Kingdom (UK)	SP	A 1% increase in the probability of delay of 30 min. or more is equivalent to \$0.60 - \$2.41 per transport
Bruzelius, 2001*	1989-1990	Shippers, Sweden	SP	A 1% increase in the frequency of delays \$4.69 - \$43.68 per transport
Fowkes et al., 2001*	1999	Shippers and Carriers, UK	SP	For deviations from the scheduled departure time, \$90/ transport hour
Hague Consulting Group, 1992a*	1991-1992	The Netherlands, shippers and carriers for road, rail and inland waterways	SP	An increase in the percentage of shipments not on time of 10% (e.g. from 10% to 11% or 90% to 99%) is equally as bad as 5-8% higher transport costs.
Hague Consulting Group, 1992b*	1992	The Netherlands, Germany and France	SP	A decrease in the probability of delay by 10 index points (e.g. from 15% to 5%) is worth \$0.01 to \$0.04 per ton-km
RAND Europe et al., 2004*	2004	The Netherlands, shippers and carriers	SP/RP	An increase in the percentage of shipments not on time of 10% (e.g. from 10% to 11% or 90% to 99%) is equivalent to \$2.37 per transport
Small et al., 1999*	1999	USA, carriers	SP	A one hour delay is worth \$526.62 per transport
Watson et al. 1974**		USA, large household appliance shippers	RP	Willing to pay \$45.98 to reduce standard deviation of travel time by one day
Winston, 1981**		USA: unregulated agriculture	RP	Willing to pay \$541.36 to reduce standard deviation of transit time by one day
Winston, 1981**		USA: Regulated agriculture	RP	Willing to pay \$5,507 to reduce standard deviation of transit time by one day for the regulated agriculture industries
Winston, 1981**		USA: Stone, clay and glass products	RP	Willing to pay \$4,345 to reduce standard deviation of transit time by one day for stone, clay and glass products

TABLE 1-2: Value of Freight Travel Time Reliability (VOFTTR) (2010 \$USD)
(continued)

Source	Survey Date	Criteria (Industry/Region)	Collection Method	Value
Winston, 1981**		USA: Primary and fabricated metals	RP	Willing to pay \$1,714 to reduce standard deviation of transit time by one day for primary and fabricated metals
Wilson et al. 1986**		USA, shippers	RP	Willing to accept 1.3 extra transit days to reduce late shipments by 1%
Ogwude, 1990, 1993**		Nigeria: consumer goods	RP	Firms WTP \$0.006 (half a cent) per ton to reduce standard deviation of transit time by 1 hour
Ogwude, 1990, 1993**		Nigeria: capital goods	RP	Firms WTP \$0.00225 (a quarter of a cent) per ton to reduce standard deviation of transit time by 1 hour.
Abdelwaham and Sargious, 1992**			RP	\$433/lb per day of improved reliability
Fowkes et al., 1991**			SP	Increasing on-time deliveries by 5% was valued equivalently to a one-half day decrease in scheduled journey time.
Small et al., 1997**		Industry composite	SP	Value of reduction of late scheduled deliveries was \$497.58 per hour per truck delivery
Halse and Killi, 2011		Shippers buying transport services	SP	\$11.83/transport for every hour the standard deviation of travel time decreased; \$68.25/transport for every hour of expected delay
Halse and Killi, 2011		Own-account freight	SP	\$233.21/transport for every hour of expected delay
Halse and Killi, 2011		Transport companies	SP	\$173.54/transport for every hour of expected delay
Zamparini, Layaa, Dullaert, 2011		Tanzania, own freight account	SP	\$0.00139 per ton-km
Zamparini, Layaa, Dullaert, 2011		Tanzania, carriers	SP	\$0.00413 per ton-km
Halse, Samstad, Killi, Flugel, Ramjerdi, 2010		Norway, shippers	SP	\$11.54 per hour change in travel time standard deviation and \$386.69 per hour of unexpected delay
Halse, Samstad, Killi, Flugel, Ramjerdi, 2010		Own-account freight	SP	\$189.30 per hour of unexpected delay
Halse, Samstad, Killi, Flugel, Ramjerdi, 2010		Carriers		\$121.29 per hour of unexpected delay

SP=Stated Preference; RP=Revealed Preference

*Values calculated from table 1 in De Jong (2004a)

**Values calculated from table 2.3 in Weisbrod et al. (2001)

TABLE 1-3: Reliability Ratio (VOFTTR/VOFTT)

Source	Criteria (Industry/Region)	Value of Travel Time	Value of Travel Time Reliability	Reliability Ratio
Weisbrod, Vary, Treyz, 2001	Agriculture	\$25.07/ transport hour	\$176/transport hour	7.020
Weisbrod, Vary, Treyz, 2001	Mining	\$24.04/ transport hour	\$60.60/transport hour	2.521
Reliability Ratio Table (\$ in 2010 USD)	Manufacturing	\$25.66/ transport hour	\$222.73/transport hour	8.680
Fowkes et al., 2001*	Shippers, carriers, UK	\$95.4/transport hour	For deviations from the scheduled departure time, \$90/ transport hour	0.943
Halse and Killi, 2011	Shippers buying transport services	Value of average value of travel time (VATT): \$16.81/ transport hour	\$68.2/ transport for every hour of expected delay	4.057
Halse and Killi, 2011	Own-Freight Account	VATT: \$61.55/ transport hour	\$233.21/ transport for every hour of expected delay	3.789
Halse and Killi, 2011	Transport Companies	VATT: \$72.35/ transport hour	\$173.54/transport for every hour of expected delay	2.399
Zamparini, Layaa, Dullaert, 2011	Tanzania, own freight account	\$0.0393 per ton-km	\$0.00139 per ton-km	0.035
Zamparini, Layaa, Dullaert, 2011	Tanzania, carriers	\$0.1243 per ton-km	\$0.00413 per ton-km	0.033

*Values calculated from table 1 in De Jong (2004a)

CHAPTER II

WSDOT Truck Freight Highway Benefit and Economic Impacts Analysis Case Studies

Overview

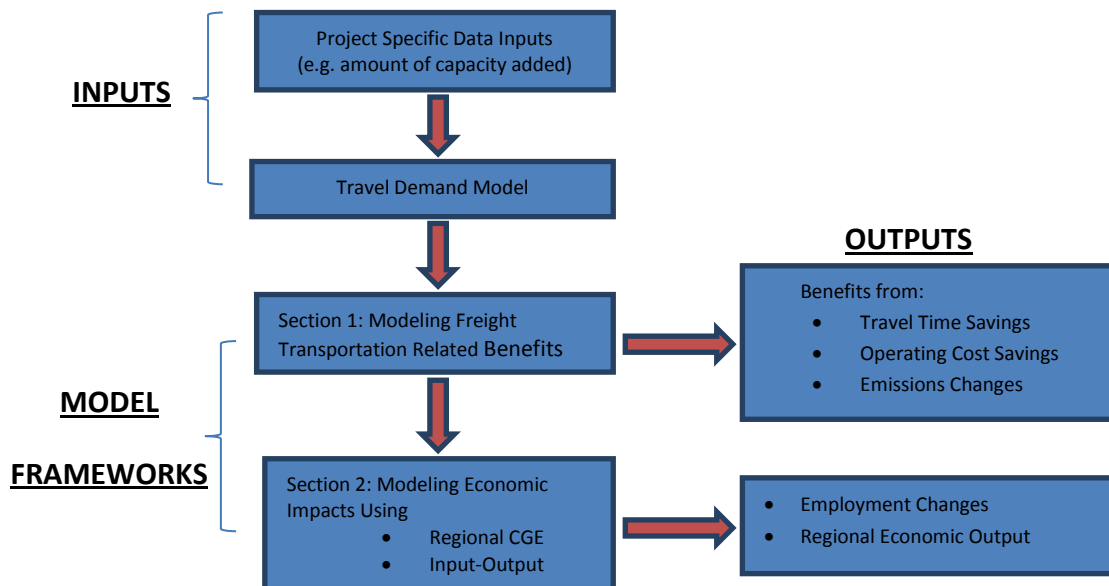
This chapter describes two case studies selected to test the proposed truck freight highway benefits and economic impacts analysis methodology. The methodology is designed to examine the full-range of freight related benefits and impacts stemming from transportation infrastructure projects. It presents the direct freight transportation-related benefit evaluation results and the economic impact of two selected case study project; A and B. The document is organized as follows: a brief overview of the analytical framework, followed by a description of the calculation of the freight transportation related benefit. Finally, the details of using a Regional Computable General Equilibrium (CGE) model and an Input-Output (I-O) model to quantify the economic impacts are described, and the results are presented. The freight transportation-related benefits and impacts are intentionally separate in this document. We are careful here to identify ‘benefits’ as those social welfare affects that may, when incorporated into the larger prioritization process of WSDOT that includes already well-established passenger benefits, be compared to the costs of an investment over the analysis period. The included benefits are developed and described in the first sections. The subsequent ‘impacts’ are then the effects that the investment has on the economy and is measured by changes in economic output and employment.

Figure 2-1 presents the workflow of the analysis process. Travel demand models (TDMs) of the selected case study regions are used to calculate the transportation benefits (Section 1), which are then used as inputs to the economic impact analysis (Section 2).

The economic impacts are estimated using the IMPLAN I-O model and Washington State CGE model.

In the Washington State Mobility Project Prioritization Process tool (MP3), travel time and speed are estimated using the speed-flow relationship of general traffic (both automobile and truck trips), which does not reflect the network effects when additional traffic is attracted to the improved segments from other roads. The proposed framework estimates the changes in truck travel time and speed using the regional travel demand models, which is able to account for network effects and consequently generates more realistic results.

FIGURE 2-1: Freight Project Impacts Analysis Workflow



Section 1 - Freight Transportation-Related Benefits

Freight transportation benefits are the direct benefits associated with freight investments, including truck travel time savings, truck operating cost savings, and truck emission changes. The calculation of benefits relies upon the TDM outputs and additional factors. This section starts with the introduction of the TDM outputs and factors used as inputs to the benefits calculation and is followed by a description of the benefits assessment methodology. Two case studies are presented to demonstrate the methodology, and this section is concluded with methodology limitations, problems encountered, and lessons learned.

Inputs

(1) Travel demand model outputs

- a. Regional TDM outputs of 2030 build and no-build scenarios for Project A.
 - i. TDM outputs consist of two major sets of link-level information: link attributes (length, capacity and facility type) and traffic performance (volume by vehicle type, travel time and speed) along the link.
 - ii. The outputs can be exported into MS Excel with five worksheets for each time period (AM, Midday, PM, Evening and Night). Traffic is modeled at the link level, and each record (row) in the spreadsheet represents the traffic condition along the link.
 - iii. Truck traffic is subdivided into three categories including: light, medium and heavy trucks.
- b. Regional TDM outputs of 2035 build and no-build scenarios for Project B.

- i. Regional TDM outputs include two sets of information: link attributes (length, capacity and facility type) and traffic performance (volume, travel time and speed by vehicle type) along each link.
- ii. The TDM outcomes can be exported to MS Excel with four worksheets for each time period (AM, Midday, PM and Night). Traffic is modeled at the link level, and each record (row) in the spreadsheet represents the traffic condition along one link.
- iii. Truck traffic is modeled as a single category.

(2) Parameters for freight transportation benefits calculation

- a. Value of truck travel time: Value of truck travel time is used to monetize the travel time savings. The values were retrieved from “Assessing Cost of Travel, Annual Update” published by WSDOT in April 2009 as shown in Table 2-1. Note that the values of travel time used for the calculation (presented in Table 2-1) are different from the values used in the Region A TDM model (\$23, \$36 and \$60 for light, medium and heavy trucks), which support the truck route choices assignment.

TABLE 2-1: Value of Truck Travel Time (\$/hour in 2008\$)^a

	Light Truck	Mixed	Heavy Truck
Region A	20.8	22.2	27.7
Statewide	20.5	21.8	26.8

- b. Truck operating cost: Operating cost per hour is used to monetize the truck operating time savings. The value was retrieved from “Assessing Cost of Travel, Annual Update” as well, and presented in Table 2-2. Both values of truck travel time and truck operating cost were analyzed for light, mixed and heavy duty trucks for both the Region A and statewide. Since the Region B TDM models truck traffic as a single category, the values for statewide mixed truck were used to calculate the travel time savings and truck operating cost savings in that case.

TABLE 2-2: Hourly-based Truck Operating Cost (\$/hour in 2008\$)

	Light Truck	Mixed	Heavy Truck
Region A	33.8	36.6	48.0
Statewide	33.8	36.6	48.0

- c. Emissions rates: Emission rates are used to estimate the truck emissions at various travel speeds. The emission rates (tons/mile) used in the case studies are the 2020 Puget Sound region emission rates estimated by PSRC using MOBILE 6.2 and MOVES demo version developed by US

^a Washington State Department of Transportation, Assessing Cost of Travel Annual Update, April 2009

It should be noted that WSDOT estimated the value of truck travel time and truck operating cost for light, mixed and heavy trucks respectively, and trucks are classified by vehicle gross weight. However, the classification criteria are not the same as the values used in the Region A TDM. WSDOT employed 26,000 lbs. as the threshold. Region A defined light trucks as four or more tires, two axles, and less than 16,000 lbs. gross weight; medium truck as single unit, six or more tires, two to four axles and 16,000 to 52,000 lbs. gross vehicle weight; and heavy trucks as double or triple unit, combinations, five or more axles, and greater than 52,000 lbs. gross weight. In the two case studies, we used the light, mixed, and heavy truck values estimated by WSDOT to estimate the travel time savings and operating cost savings for light, medium and heavy trucks modeled in the Region A TDM, and statewide mixed truck value for trucks modeled in the Region B TDM.

Environmental Protection Agency (EPA)

(<http://www.epa.gov/oms/m6.htm>). The values vary depending on the network facility type (freeway and arterial), truck type (light, medium and heavy), and operating speed (all included in TDM outputs).

- d. Emission costs: Emission costs (dollar/ton) are used to monetize the emission reduction. The cost per unit (dollar/ton) used in the case study is consistent with the value used in the PSRC benefit-cost analysis (BCA) tool, as presented in Table 2-3. Emission cost estimates range broadly depending on the analysis methodologies. The values employed here present a middle of the range of available estimates.

TABLE 2-3: Emissions Cost per Ton (\$/ton in 2008 dollars)

	CO ₂	CO	NO _x	VOC	PM _{2.5}
Emission Cost	40	475.02	12,250.64	9,750.51	8,125.42

- e. Discount rate: A discount rate is employed to account for inflation. The value used in the two case studies is 4 percent, which is consistent with the current value used by WSDOT.
- f. Annual/daily benefits: Travel demand model outputs represent the daily transportation performance, and an “annual/daily benefits” parameter is designed to convert the daily benefits to annual benefits. The default value is 260 days/year, consistent with WSDOT current practice.

Methodology

The freight transportation benefits consist of travel time savings, truck operating cost savings, and truck emission impacts. This section first discusses the methodologies

employed for estimating the forecast year transportation benefits based on TDM outputs. The forecast year is defined as the future year modeled by the regional TDMs. Following the forecast-year benefits estimation, is the method for estimating analysis period benefits from the single forecast year benefits. Finally, the discounting of annual benefits to account for inflation is discussed.

Forecast Year Transportation Benefits Modeling

Travel Time Savings

Truck travel time savings are calculated based upon the change in system VHT and value of travel time as shown in equation 2-1. The TDM outputs provide link level travel time and traffic volume, from which the link level truck VHT can be computed by multiplying travel time with traffic volume. The system total VHT is the sum of the link level VHT. Value of truck travel time is predefined and presented in Table 2-1.

$$B_T = \Delta VHT \times C_T, \quad \text{Equation (2-1)}$$

where:

B_T = Travel time saving (dollars)

ΔVHT = Changes in system VHT (hr)

C_T = Value of truck travel time (dollars/hr)

Operating Cost Savings

Truck operating cost savings are estimated using changes in system VHT and truck operating cost per hour assessed by WSDOT:

$$B_o = \Delta VHT \times C_o , \quad \text{Equation (2-2)}$$

where:

B_o = Truck operating cost savings (dollars)

C_o = Truck operating cost per hour shown in Table 2 (dollars/hr)

Emission Impacts

The value of any change in emissions from the project is evaluated as tons of desired air pollutants and the corresponding cost per ton. The amount of pollutions is calculated by multiplying the truck vehicle miles traveled (VMT) (mile) and emission rates (tons/mile). The link level VMT is computed by multiplying the link length and truck volume, which are both included in the TDM outputs. The emission rates employed in the two case studies are estimated using EPA Mobile 6.2 and MOVES demo version software. In future application, the local emission rates can be estimated using the latest EPA MOVES software. The values vary depending on the truck operating speed, truck type, and transportation facility type that all are included in TDM outputs.

$$B_E = \sum_{j=0}^4 \sum_{k=0}^n (VMT_{k,1} \times e_{j1} - VMT_{k,2} \times e_{j2}) \times C_j , \quad \text{Equation (2-3)}$$

where:

B_E = change in emission costs (dollars)

k = number of links of the entire network

$$j = \begin{cases} 0, & \text{Carbon Dioxide} \\ 1, & \text{Carbon Monoxide} \\ 2, & \text{Nitrogen Oxide} \\ 3, & \text{Volatile Organic Compound} \\ 4, & \text{Particulate 2.5} \end{cases}$$

e_{j1} = Pre-investment emission rates of pollutant j (tons/mile), determined by truck type, speed, and facility type

e_{j2} = Post-investment emission rate of pollutant j (tons/mile)

$VM_{T_{k,1}}$ = pre-investment truck vehicle miles traveled on link K

$VM_{T_{k,2}}$ = post-investment truck vehicle miles traveled on link K

C_j = cost per ton of pollutant j shown in Table 3 (dollars/ton)

Total Forecast Year Daily Benefits

The sum of the three benefits calculated using equation 2-1 to 2-3 is the forecast year daily freight transportation benefits, as shown in equation 2-4.

$$B_{daily} = B_T + B_O + B_E, \quad \text{(Equation 2-4)}$$

where:

B_{daily} = forecast year daily benefits

Total Forecast Year Annual Benefits

The forecast year annual benefits are calculated by multiplying the daily benefits with the pre-defined “Annual/daily benefits” parameter.

$$B_{forecast} = B_{daily} \times Annual / daily Benefits , \quad (\text{Equation 2-5})$$

where:

$B_{forecast}$ = forecast year annual benefits

Annual / daily Benefits = number of days per year, and the default value is 260 days/year, consistent with the current value used in the MP3 tool.

Estimating Project Analysis Period Benefits from a Single Forecast Year Benefits

Other years’ benefits are interpolated from the forecast year results with the assumption that the first year benefits equal to the forecast year benefits divided by the number of years from the first year to the forecast year. The annual benefits increase at a constant amount equal to the first year benefits. Therefore the annual benefits for any other year can be calculated by multiplying the number of years with the first year benefits. The calculation is shown in equation 2-6.

$$B_1 = \frac{B_{forecast}}{n}$$
$$B_i = i \times B_1, \quad i > 1 \quad , \quad (\text{Equation 2-6})$$

where:

B_i = the i^{th} year annual benefits

n = number of years from the first year to the forecast year

Discounting Benefits

In order to account for inflation, all benefits are converted to constant dollars using the discount rate of 4 percent, as shown in equation 2-7.

$$B'_i = \frac{B_i}{(1 + \alpha)^t}, \quad (\text{Equation 2-7})$$

where:

B'_i = net present value of the i^{th} year benefits

t = time of the cash flow

α = discount rate, 4 percent

Total Benefits over Project Analysis Period

$$B = \sum_{i=1}^n B'_i, \quad (\text{Equation 2-8})$$

where:

B = total freight transportation benefits over the analysis period

Results: Freight Transportation Related Benefits

Project A

Project Description

Project A was selected as one of the two case studies to test the proposed methodology. The extension project seeks to fill a missing link in the state's highway network. An identified tolling scenario was analyzed for this case study. The scenario assumes building one lane in each direction along segments of the highway, and two lanes in each direction between along another (a six-mile long highway). The scenario will additionally build five partial interchanges. The test scenario additionally assumed that the transit/HOV lane will be converted from the current requirement of at least 2 travelers (a 2+ person HOV lane) to 3 travelers (a 3+ person HOV lane).

The travel performances in the 2030 no-build and build scenarios were modeled by WSDOT's Urban Planning Office (UPO) using the Region A TDM. Truck travel demand in the TDM is pre-defined based on household and employment data. Region A's TDM is a four step gravity model for travel forecasting and has seven basic components: household vehicle availability, person trip generation, trip distribution, mode choice, time of day, truck model, and trip assignment. Within the model, truck trips are generated and attracted at different rates according to the employment categories. For the same forecast year, the number of truck trips remains the same for the no-build scenario and build scenario, and is not affected by highway network improvement. However, truck trips may be re-distributed among origin-distribution (O-D) pairs and re-assigned to other links in the updated network of build scenario, and therefore, there may be changes in truck travel

time, travel distance and speed along each link. Trucks in the TDM are subdivided into three categories: light, medium and heavy. Truck traffic is modeled during five time periods including: AM, Midday, PM, Evening, and Night. The TDM converts truck trips to passenger car equivalents during trip assignment, and assumes heavy and medium trucks travel at slower speed compared to passenger cars while formulating the travel cost function. However, the model generates the same travel time and travel speed for all three types of trucks and passenger cars.

Results

The project benefits are estimated based on the project schedule assumption that construction would be completed by 2019, and the project analysis period is from 2020 to 2040.

The 2030 build and no-build scenarios were modeled using the Region A TDM, and the forecast year (2030) benefits were calculated based on the TDM outputs. Benefits in other years were interpolated from the 2030 benefits. Benefits over the project analysis period for three types of trucks are presented in Table 2-4.

TABLE 2-4: Summary of Transportation Related Benefits of Project A Over the Analysis Period 2020-2040

Present Value of Benefits	2010 Dollars
Start Year	2020
End Year	2040
Benefit Category	
Light Truck Travel Time Benefits	\$ 16,870,448
Medium Truck Travel Time Benefits	\$ 3,734,396
Heavy Truck Travel Time Benefits	\$ 5,813,874
Light Truck Operating Cost Benefits	\$ 27,414,479
Medium Truck Operating Cost Benefits	\$ 6,156,708
Heavy Truck Operating Cost Benefits	\$ 10,074,584
Light Truck Emission Impacts	\$ 87,202
Medium Truck Emission Impacts	\$ 76,757
Heavy Truck Emission Impacts	\$ 1,438,546
Total	\$ 71,666,995

Comparison with other studies

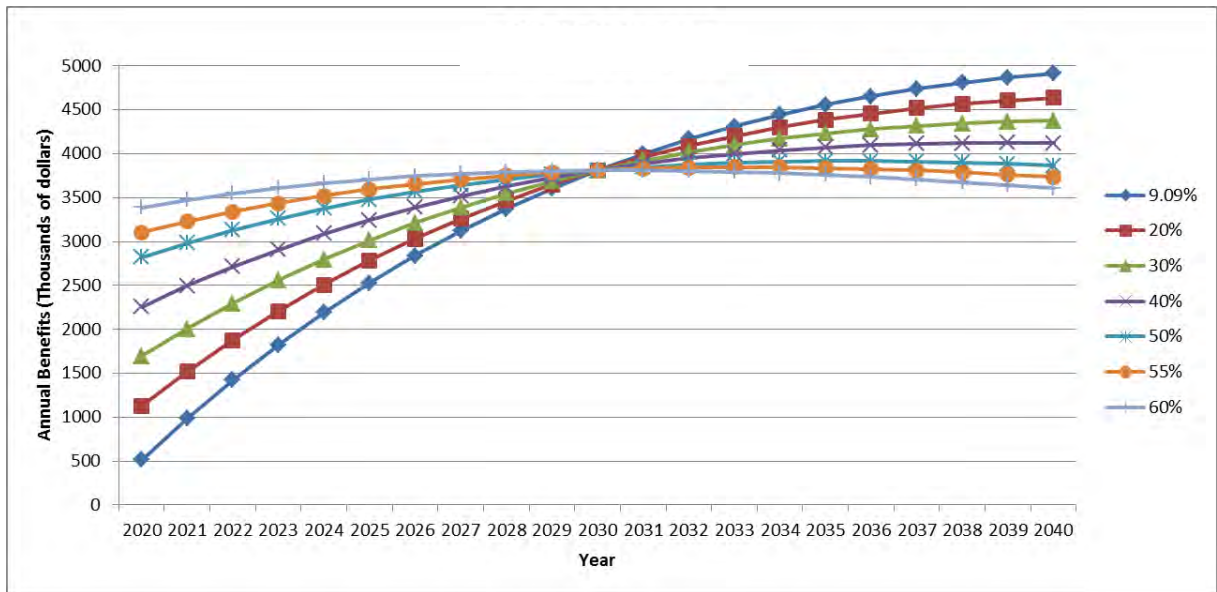
The result calculated by the proposed method is also compared with two other similar benefit-cost analyses. These analyses are identified as performed by Analyst 1 and Analyst 2. The results are comparable and details of the comparison are presented in Appendix 2-1.

Sensitivity Analysis

A sensitivity analysis of the first year benefits calculation method was conducted to understand its impacts on annual benefits over years. The method employed in the case study assumes the first year (2020) benefits are 9.1 percent (1/11) of the forecast year (2030) benefits. A similar project benefit-cost analysis conducted by Analyst 2 indicates that the 2020 benefit takes 55 percent of 2040 benefits calculated based on Region A TDM outputs. Due to the lack of data required to model the first year situation using the TDM in the case study, a sensitivity analysis was performed to examine the impacts of

different fractions (9.1 percent, 20 percent, 30 percent, 40 percent, 55 percent and 60 percent) on interpolation results. Figure 2-2 plots the benefits over the project analysis period using different fractions. It is noted from the figure that lower fractions generate smaller first year benefits, but lead to higher annual increase rates. Since the forecast year is in the middle of the analysis period, the total benefits (area under curves) over the 20-year time period are close regardless of the fractions used. The total benefits over the analysis period with fractions of 9.1 percent and 60 percent are \$71.7 and \$77.6 million respectively.

FIGURE 2-2: Sensitivity Analysis of First Year Benefits Calculation Method



Project B

Project description

Project B was selected as the second case study to evaluate the capability of the proposed framework in evaluating the project cost efficiency. The Highway is 9.7 mile critical

truck freight corridor serving approximately 5,000 to 7,000 trucks daily in 2011. It is also a strategic freight corridor carrying international and domestic trade. Freight demand in this area is projected to increase by 30 percent over the next 10 years, which will lead to considerable congestion and other negative impacts if the segment cannot accommodate the growing passenger and freight demand. Project B will add two additional lanes (one lane each direction). The impact of the project is modeled using the associated Regional TDM.

Similar to the Region A TDM, Region B's TDM is a standard four-step gravity model, which includes trip generation, trip distribution, mode choice and network assignment components. The truck demand is determined by household and employment data.

Therefore no induced demand will be captured by the model. Different from the Region A model, truck trips in the Region B model are modeled as a single category, and are evaluated in four time periods including AM, Midday, PM and Night. The model converts truck counts to passenger car equivalents and employs the same impedance function for passenger car and trucks. The model estimates the same passenger car and truck speed, unless the passenger car speed is greater than the truck speed limit, and in this case the truck speed limit is assigned as the truck speed.

Results

The projected 2035 regional TDM outputs of build and no-build scenarios were provided by WSDOT using the Region B TDM. We calculated the changes in system total truck VHT and truck VMT to estimate the travel time savings, truck operating cost savings, and emission changes associated with this highway widening project. Construction is expected to be completed in 2014, thus benefits were estimated from 2015 to 2035.

Details of the calculated results are presented in Table 2-5. Benefits in other years were calculated with the same assumption of Project A.

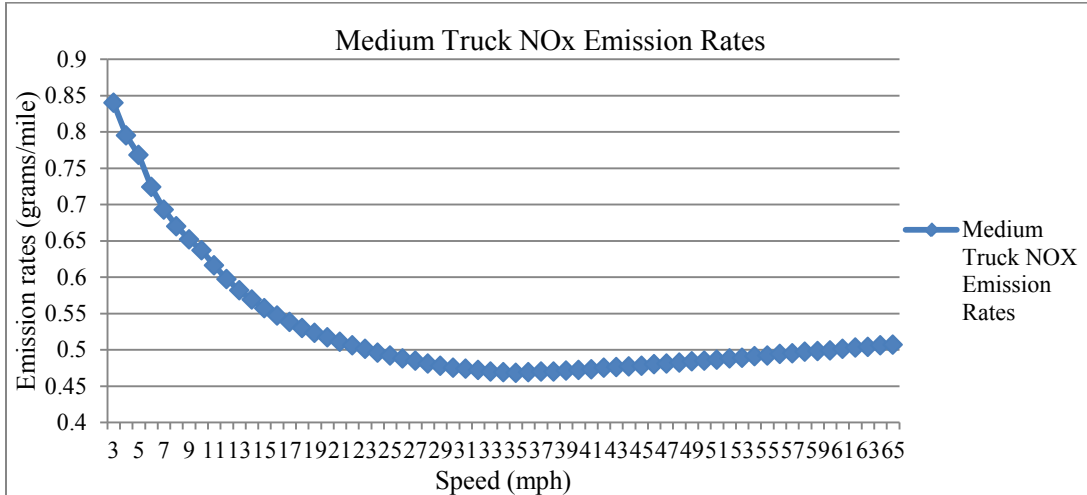
TABLE 2-5: Summary of Transportation Related Benefits of Project B Over Analysis Period (2015-2035)

Present Value of Benefits	2010	Dollars
Start Year	2015	
End Year	2035	
Benefit Category		
Truck Travel Time Benefits		\$ 9,255,929
Truck Operating Cost Benefits		\$ 15,539,771
Truck Emission Impacts		\$ (73,837) ^a
Total		\$ 24,721,864

^a The emission impact in red represents negative value.

It is noted the light and medium truck emission impacts were negative, though the traffic performance was improved after the investment. This is due to vehicle emissions increasing with higher operating speed. For example, Figure 2-3 presents the medium truck NOx emission rates in 2020 at different travel speed estimates. The emission rate drops while operating speed increase from 0 to 30 mph, and grows again when the speed raise from 30 mph to 60 mph.

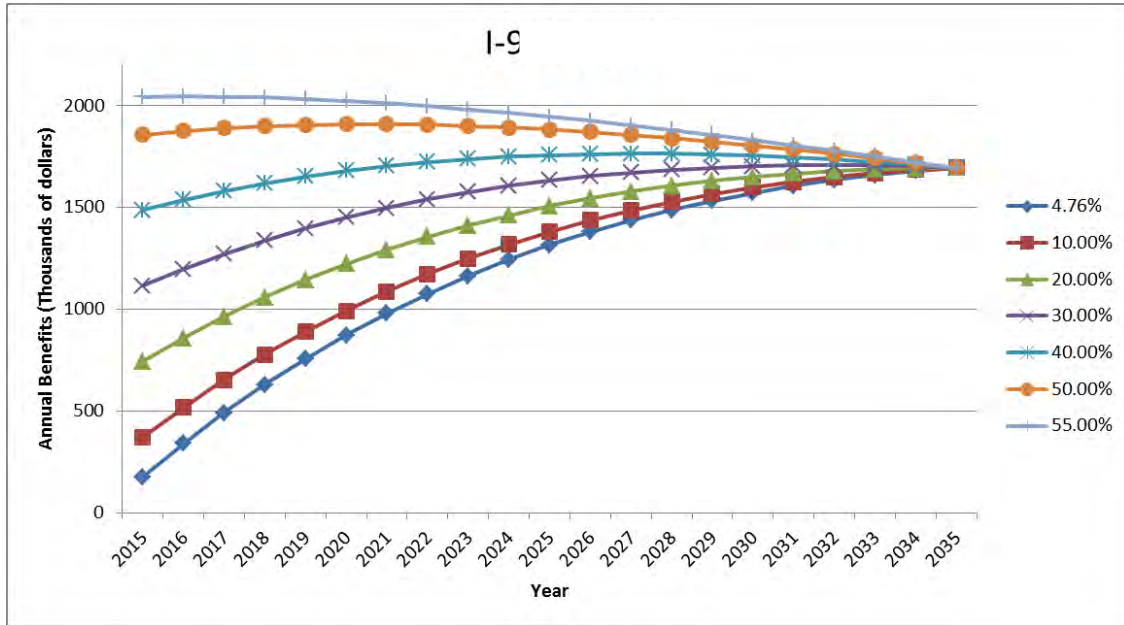
FIGURE 2-3: Medium Truck NO_x Emission Rates on Arterial Road



Sensitivity Analysis

Similar to Project A, a sensitivity analysis of the impact of the first year benefits calculation method was conducted. Fractions used to estimate the first year benefits were 4.8 percent (1/21), 10 percent, 20 percent, 30 percent, 40 percent, 50 percent and 55 percent. The interpolation results are presented in Figure 2-4. Different from the Project A results, the total benefits over the analysis period vary substantially depending on the fraction used. The total benefits from 2015 to 2035 are \$25 million when the fraction of 4.8 percent is used, and increase to \$40 million using fraction of 55 percent. This is due to the use of 2035 as the forecast year, which is the last year of the analysis period, rather than a mid-period year, as was the case with Project A.

FIGURE 2-4: Sensitivity Analysis of Frist Year Benefits Calculation Method



Discussion and Recommendations

1. Forecast year benefits calculation—strengths and limitations of using TDMs

The forecast year transportation related benefits modeling relies upon the TDMs since the changes in freight performance are estimated using TDM outputs. We use this approach, rather than using a segment-based volume capacity ratio (v/c) adjustment, so that the network effects can be captured. In a TDM, segment performance alters route choice, and network flows can be redistributed when performance changes. This is a dramatic improvement over a segment-based approach. Traffic along each segment will be updated until new system equilibrium is reached under the assumption that travelers always pursue maximum utility. This dynamic cannot be implemented with a segment based v/c and speed relationship. The TDMs used by MPOs are state of the practice,

vettted, validated and tested, and regularly applied for transportation planning applications.

While the use of a TDM presents a dramatic improvement over the status-quo, there are some significant limitations to using these models in a freight benefit-cost analysis.

These are discussed below.

(1) Some TDMs do not have sufficient modeling capability to be used for freight project benefits analysis.

Most MPOs have their own regional TDMs, however some of them are not ready to be used in the proposed methodology. For instance, Cowlitz-Wahkiakum Council of Governments' and Wenatchee Valley Transportation Council's TDM only evaluate traffic in PM peak hours and do not have daily assignment to support the transportation related benefits calculation. Whatcom Council of Governments' travel demand model does not have a validated truck module using survey data and is not recommended for use to evaluate freight projects. The model applicability will need to be judged on a case by case basis.

(2) Freight demand in household and employment-based TDM is fixed.

Freight demand in both Regional TDMs are determined by household and employment data, and is independent of traffic conditions. Although in reality, additional truck trips may be generated as a result of transportation costs reduction and service improvement, this induced travel demand is not captured by the TDM. This demand may have negative

impacts on system performance, thus current TDMs may over-estimate the transportation related benefits associated with investments.

(3) Model results are a function of user defined parameters.

This is not unique to TDMs, but is true of any modeling framework. TDM outputs are dependent on parameters and factors set by analysts. For instance, the value of truck travel time is a user input, and this value affects route choice when a toll road is an option for truck drivers. The route choices of all drivers affect system performance, and therefore final outcomes. In order to compare the outputs from two different TDMs, the value of these parameters should be investigated and compared.

(4) Truck speed is deterministic.

The travel speed during each time interval is deterministic, and TDMs cannot account for the speed variability of different vehicle types.

2. Comparability of the Region A TDM and Region B TDM

Project prioritization depends upon comparing the results of different TDM outputs. Both regional TDM's are household and employment-based TDMs. Below we investigate the model assumptions and inputs of each model to analyze the comparability of the two models.

Region B TMD assumptions and inputs

Region B TDM model is a household and employment-based model and requires specific and accurate land use data in the form of employees, dwelling units, hotel rooms and schools.

Region B used the Board of County Commissioners Population Allocation Resolution as population forecast. The Population Allocation Resolution also identifies population growth targets by jurisdiction, Urban Growth Areas, Joint Planning Areas, and rural areas.

Because the model uses dwelling units as input rather than population, Region B derived dwelling units from the population forecast. Region B provided current dwelling unit numbers to each jurisdiction, and asked them to convert their population targets into dwelling units using ratios of persons per household, and place their dwelling unit allocation by transportation analysis zone (TAZ) in future years. The regional dwelling unit growth between 2008 and 2030 is 27 percent, with an annual growth rate of 1.10 percent.

Employment growth is derived using a flat growth rate of 1.365 percent compounded annually. This rate was arrived at by referencing a variety of employment sources (US Bureau of Labor Statistics, US Census Bureau Longitudinal Employer-Household Dynamics, Quarterly Workforce Indicators, ESD, IMD). Region B then offered jurisdictions the option to apply the growth rate uniformly among their TAZs or to hand

place 30 percent of their employment growth in areas they expect to see higher than normal growth. If the agency chose to have the uniform rate applied, Region B simply used the 1.365 percent annual growth rate to calculate future employment. If jurisdictions chose to hand place growth, they were only allowed to place their specific growth rate to 30 percent of the base year employment. Region B then applied the 1.365 percent annual growth rate to the remaining 70 percent of the base year employment to arrive at the future year employment for TAZs.

	2008	2035	Growth	Estimated annual growth rate
Employment	204,141	274,270	34%	1.10%
Household	221,453	327,120	48%	1.46%

Region A TDM assumptions and inputs

Region A used land use and economic forecasting models to forecast population, households and employment. A two-part "top-down" approach was adopted: prior to developing forecasts for individual Forecast Analysis Zones (FAZs), a Regional Forecast was prepared using a variation of an Economic Forecaster (EF) econometric model. The EF model produces estimates of population, households and employment for each of the four counties in the region s as a whole. Region A then employs a different set of models, DRAM (Disaggregate Residential Allocation Model) and EMPAL (Employment Allocation Model), to arrive at future year forecasts for individual FAZs.

Regional Council population forecasts have different uses from OFM forecasts: OFM forecasts are for population at the county level only, and are mandated for use in jurisdiction and county comprehensive planning updates. The Regional Council prepares

small area forecasts of population, households and employment in order to meet the requirements of federal legislation and data needs for land use and transportation modeling. Although differences exist, the county-level population forecasts produced by the Region A modeling process are generally consistent with the OFM population forecasts.

The regional employment and household forecast used as inputs into Region A TDM is as follows:

	2008	2030	Growth	Estimated annual growth rate
Employment	1,765,592	2,427,457	37.5%	1.46%
Household	1,386,593	1,920,842	38.5%	1.49%

Region A and B TDM comparability

Although the regions used different methods to forecast population and employment growth, their population forecasts are generally consistent with OFM forecast. The household growth (1.46 percent annual growth rate) used in Region A TDM model is a little higher than Region B TDM model (1.1 percent), but the employment growth used in the two models are almost the same. Not to mention, we expect that these regions may have different economic outlooks. The TDM takes the employment and population data as inputs to develop future travel demand. The truck demand growth generated in two TDM models is as follows:

Region A TDM model:	2008	2035	Growth	Annual growth rate
Total truck demand (in trips)	173,480	238,920	37.7%	1.19%

Region B TDM model:	2008	2035	Growth	Annual growth rate
Total truck demand (in trips)	453,587	595,109	31.2%	1.24%

The annual truck growth rates produced in the two models are very consistent. The two models are both four-step models with truck traffic generated by household and employment. Meanwhile, these two models are validated and tested, and are regularly used to model regional traffic.

3. Annual benefits estimation – interpolation methods

The method used in the two case studies was to assume the first-year benefits are equal to the forecast-year benefits divided by the number of years between the first year and the forecast year. For Project A, the forecast year is 2030, for Project B the forecast year is 2035. TDM outputs were already available for these future years and did not require additional travel demand model runs.

The analysis period for Project A is 2020 to 2040; the analysis period for Project B is 2015 to 2035. We require some methods for estimating the project analysis period benefits from the forecast-year and first-year benefits. We assume the annual benefits increase at a constant amount equal to the first-year benefits. The limitation of this assumption is that annual benefits increase linearly, however actual benefits in the first few years may be larger than in later years as travel demand is smaller in the first few years.

In the future, we recommend modeling the first-year benefits using TDM outputs, as well as modeling every five years, to get a more realistic result. In the meantime, if the model does not have such capability, the method described above can be applied.

4. Future work

(1) Requirement of regional data.

The benefits calculation is based upon a set of parameters, e.g. value of travel time, truck operating costs and emission costs. These parameters vary depending on a number of factors including truck types, infrastructure types, and local conditions. For instance, trucks are modeled as a single category in the Region B TDM, but as three subcategories in the Region A TDM, and therefore, different values of truck travel time should be applied to estimate the travel time savings. Another example is the emission rates. The truck emission rates employed in the case study were estimated using EPA MOBILE 6.2 and MOVES demo version software Region A, and should be updated using the latest MOVES model with local information.

(2) Truck safety improvement analysis.

Although safety improvement has been considered in the current WSDOT MP3 tool, the pre-defined incident reduction rates can only be applied to certain types of investments, e.g. adding stop sign or adding ramp metering. In addition, these rates are not truck traffic specific. Changes in the number of truck-involved accidents can be estimated based on the changes in truck performance (e.g. v/c), which can be estimated using TDMs. The calculation of incident reduction also requires the no-build scenario link-level traffic

accident statistics. Safety is not included in this phase since such accident statistics are not readily available. To capture the freight safety improvement, either the incident statistics need to be prepared or other methods should to be proposed in the future research.

(3) Travel time reliability improvement analysis.

Travel time reliability is excluded due to insufficient regional data sources. Travel time is currently evaluated using TDMs. However, the travel time estimates estimated by TDMs are deterministic and cannot reflect the variability. To capture such variability, many runs of the TDMs with different inputs, e.g. demand following some distribution, are required. In addition, the values of truck travel time reliability that exist are unsatisfactory. The truck travel time reliability evaluation will be included in the next phase of this research.

5. Challenges

(1) Region of analysis.

We had discussions on whether we should run the TDMs for the entire region or a smaller region covering the network improvement. The major concern of running the model for the entire region is that it may dilute the impacts of the project. However, we decided to run the model for the entire region since traffic may be attracted to the improved segments from other roads, and the full model can better capture such trip re-distribution.

(2) Lack of expertise in model users.

The proposed method relies upon the output of regional TDMs, which are provided by local transportation agencies. However, the lack of expertise in model users required analysts to spend additional efforts on understanding the assumptions and structure of the model, and ensuring the results are correct and reliable. For instance, there were a series of misunderstandings regarding induced demand after one model user mistakenly communicated that the model did have demand elasticity. We noted that the system travel time of the build scenario was greater than the value of the no-build scenario, which is unreasonable if travel demand is fixed. We were told initially that the travel time increasing was caused by induced travel demand. However, this is not consistent with the principle that travel demand of household and employment-based model should be fixed. After communicating with the initial model developers, we learned that this TDM does not account for the induced demand, and the unreasonable results we got were likely caused by network coding and traffic assignment non-convergence. Meanwhile, the unreasonably high travel time estimates along several links may be also caused by the network coding errors. These problems were solved by using an updated version of the TDM.

(3) Lack of local data.

The calculation of freight benefits depends upon several parameters, including the truck value of travel time, operating cost per hour and emission rates. The truck value of travel time and operating cost per hour estimated by WSDOT were used in the case study. Truck classification in the WSDOT analysis was determined by the gross truck weights.

However, this classification is not consistent with the Region A TDM truck classification method. We are using WSDOT values in the Project A case study, but values based on Region A's truck classification should be used in future regional projects analysis.

Similarly, Region B TDM models truck as a single category, and we used the values of mixed trucks (light and heavy trucks) in the calculation. In addition, we used the 2020 Puget Sound region truck emission rates for the emission impact analysis. These values were generated by PSRC using the MOBILE 6.2 and MOVES demo version software. We do not have the emission rates for Region B, and therefore we estimated Project B impacts on truck emission using the Puget Sound region values.

(4) Lack of first year TDM outputs.

Most benefit-cost analysis applications, including WSDOT current MP3 tool, estimate both the first-year and final-year benefits, and assume the annual benefits increase at a constant amount to estimate benefits over the analysis periods. However, only forecast year TDM outputs were available for the two case studies presented in this document. We requested the first-year TDMs, but were told such data was not available. Thus we conducted the sensitivity analyses to evaluate the impacts of the first-year benefits calculation method.

(5) Different analysis periods.

Project A modeled 2030 build and no-build scenarios, and the first year after project implementation is 2020, thus the analysis period is 11-year. For Project B, the future year modeled by the TDM is 2035, and the first year after project implementation is 2015, and

therefore the project analysis period is 21 years. We calculated the total benefits over the analysis period for the two projects respectively and found the results were not comparable due to different analysis periods. To ensure results of the two case studies are comparable, we extended the analysis period of the Project A to 2040 to allow the same analysis period.

6. Lessons learned

- (1)** The household and employment-based TDMs do not account for induced demand, and therefore the truck travel demand in the build and no build scenarios should be the same. However, the truck travel performance is expected to be improved in the build scenario.
- (2)** Not all TDM modelers are experts. Thus analysts need to understand the assumptions, inputs and parameters of the TDMs. Meanwhile, the TDMs' outputs need to be verified. Analysts should check if there exists unreasonable travel time/speed along segments, and if the truck performance is improved in the build scenario.
- (3)** Before conducting the freight benefit calculations, the assumptions of land use, household and employment growth rate of each TDM should be examined to ensure the comparability among different models. Meanwhile, model parameters, e.g. value of truck travel time which is used for truck trip assignment, should represent local conditions.
- (4)** The length of the project analysis periods of each evaluated project should be the same to ensure comparable results, e.g. 20 years.

- (5) Freight transportation-related benefits should be added to the established passenger car benefits before comparing with the project costs to allow reasonable B/C analysis.
- (6) Appropriate local data (value of truck travel time, operating cost, and emission rates) of different types of truck and time period should be investigated before calculating the direct freight benefits.
- (7) We recommend having both the first and end year TDM outputs to allow more realistic analyses.

Section 2 - Regional Economic Impacts

Benefit Cost Analyses (BCA) such as those developed in the previous section and those widely used by transportation agencies, including WSDOT, provide a necessary first step in understanding whether society is better off under a proposed investment, than where the investment is not made. However, a standalone BCA falls short in allowing an agency to consider the resultant increases in productivity and economic efficiency from an infrastructure investment. These productivity considerations are becoming a routine necessity under new federal transportation bills (e.g. MAP-21).

In addition to those direct benefits described previously, there are additional economic impacts as businesses, consumers and others respond to the transportation investments and improvements. Industry responses to the increased transportation efficiencies may include such reactions as job creation, wage level changes, business activity, and tax base expansion resulting from increased accessibility and connectivity. These responses are

captured via an Economic Impact Analysis (EIA) that enables the enumeration of the likely change in the economy as a result of the benefits identified previously.

Substantial use of statistical models representing the flow of dollars between industries has been used to relate transportation investments to productivity and employment. Abilities garnered from the age of simulation models in the 1980s have allowed transportation planners and academics to forecast transportation project impacts on regional growth. The earliest among these models were based on the input-output models (I-O) first developed by the Nobel Prize winning economist Wassily Leontief. These models permit the analyst to empirically identify and calculate the relationships between various aspects of a given economy, including production, consumption and all inter-industry relationships associated with the factors of production (labor and capital) and consumption (earnings or payments).

Here, the implications of implementing an I-O modeling framework versus that of a regional computable general equilibrium model (CGE) of Washington State's economy are examined. Both frameworks aim to capture interactions and estimate regional economic impacts. Fixed-price, I-O models are frequently used by regional policy analysts for their simplicity and presumed reliability in long-run applications^a. CGE models do not contain the restrictive, fixed-price assumptions and are thus considered to be a more realistic real-world model, particularly in short-run considerations (Cassey et al., 2011). The primary drawback of traditional I-O models is the fact that they offer at

^a Long-run considerations assume that many input factors are variable, specifically that of capital and labor; alternatively, short-run implies that those factors are largely fixed.

best only a partial equilibrium response since all relative prices in the economy are fixed and any substitution of inputs not possible (which is partly why it is so much easier computationally to calculate as opposed to a vector of all feasible prices for each factor input or output). Therefore, any shock or change to the economy being analyzed (state, region or nation) coming in the form of higher taxes, increased subsidies, changes in production technology, or other typical policy applications results in an economic response that never changes the ratio of inputs (for example labor and capital). In general, and certainly at a microeconomic level, we would expect that businesses make adjustments to the production decisions as these relative prices of inputs begin to change which then effects their outputs as well. CGE models offer considerably more flexibility (for example allowing relative prices to change), but are therefore computationally more demanding and also require considerably more economic acumen by the user in consideration of the specified model inputs.

The underlying premise of all CGE models is the assumption that if all markets in a given economy are in equilibrium, then any individual market will also be in equilibrium and therefore a market clearing price and quantity exists for any individual sector of the economy, as well as the whole regional economy. The conceptual flow of activities is relatively simple and straightforward with all firms in an economy producing their own unique goods from inputs (labor and capital) which are provided by the households. These goods, services and commodities are then either utilized as inputs for other firms or consumed by households at the respective market clearing price.

Data Inputs and Model Initiation

Data for both the I-O and CGE models are generated from the most recent IMPLAN (2010) data. Social Accounting Matrices (SAMs) are generated within IMPLAN and used internally for I-O, and exported to the Generalized Algebraic Modeling System (GAMS) for modeling in the CGE framework. Subsequently, both impact models are generated from the same data source, increasing the comparable nature of the two. IMPLAN's basic structure contains 440 industries, of which we aggregate into 20 sectors in rough accordance with their 2-digit NAICS code (Table 2-6). The 20 sectors represent common industry classification aggregations that make visualization and interpretation of the model results more fluid. Despite the ability to utilize the same SAM and aggregation scheme, the model initiation cannot be implemented similarly in both frameworks. The implementation strategies for each are detailed next.

TABLE 2-6: Industry Aggregation Scheme

Aggregation Code	Freight Dependent Industries ^a	Aggregation Code	Other Industries
AGFOR	Agriculture and Forestry	INFO	Information Services
MIN	Mining	FININS	Financial and Insurance
UTIL	Utilities	REAL	Real Estate
CONST	Construction	PROTEC	Professional and Technical
MANUF	Manufacturing	MANAG	Management
WTRAD	Wholesale Trade	ADMIN	Administration
RTRAD	Retail Trade	SOCSER	Social Services
TRAWAR	Transportation and Warehousing ^b	ARTS	Arts and Entertainment
TRUCK	Transport by Truck	FOOD	Food Services
WMAN	Waste Management	OTHR	Other (Including Government)

^a Industries are classified to largely coincide with the aggregations created in the WSDOT commissioned *Cost of Congestion* study (Taylor, 2012).

^b The TRAWAR aggregation consists of all transport modes other than Transport by Truck.

Implementing the Input-Output Model

The nature of IMPLAN's I-O model framework allows an examination of only the backward linkages of industrial interaction. A backwards linkage is that connection where an increase in the output of an industry is modeled. This 'shock' results in the output of all those industries from which the affected industry procures intermediate inputs also increases. Thus, modeling a change in output of just the Transport by Truck (TRUCK) sector will not provide indication of the forward linkage effects of those who use trucks as an intermediate input for their production; thus, we cannot directly tell if there is any change in truck transport demand due to the benefits generated in the TDM. What it does do, via its backwards linkages, is produce indirect effects on those industries from whom the transport by truck sector purchases intermediate inputs. This reflects the required additional output from those sectors to meet the new input demands of the transport by truck sector.

The benefits experienced on the network by carriers are not a direct increase in their output; rather, it is an increase in their productivity. The I-O model in IMPLAN is typically shocked by simulating an increased output (An 'industry change' activity may be modeled in IMPLAN via an event that suggests an increase in sales (output) by the industry). As such, the changes in operating costs and travel time experienced by the trucking firms, as revealed by the TDM, are first converted to a reduction in cost experienced by other sectors. Next, the estimates for reduction in production costs must be converted to a change in the output of each sector and thus the amount of trucking services demanded by freight dependent and other sectors (shown in Table 2-7). By

affecting the output of freight users, the backwards linkages of the I-O model may be captured and utilized.

This conversion assumes that a reduction in operating costs and travel time results in a decrease in the price paid for freight transportation services, thus reducing production costs of all freight using sectors. We further assume that this reduction in production costs results in an increase in output by said sectors (amount is dependent upon the elasticity of output with respect to production cost) and the transportation, along with other intermediate input sectors must then follow – as per the associated backward linkages - by increasing their own output (See table 8 below). Central to the methodological steps outlined here, is the ability to assume a production cost reduction for every industry that directly purchases trucking services in a manner that is consistent with their current usage patterns. Friedlaender and Spady (1980) characterize freight transportation as a productive input that should be treated analytically like any other input. Further, they find - as have others since (Abdelwahab 1998) - own price elasticity of demand for trucking services to be near unity ($e = -1$); particularly in the Pacific Northwest. The estimated values tend to be dependent upon both commodity and region. Regional consideration in this literature is at the national level, thus providing no indication of variability of this elasticity within a state like Washington.

The functional relationship between production cost reductions experienced by each sector and their output changes is given by (Seetherman et al. 2003):

$$D_{1i} = D_{0i}(X_{1i}/X_{0i})^e, \quad (\text{Equation 2-9})$$

where,

D_{0i} = Output before Infrastructure Investment for Industrial Sector i (IMPLAN generated)

D_{1i} = Output after Infrastructure Investment for Industrial Sector i

X_{0i} = Cost of Production attributable to trucking before Infrastructure Investment for Industrial Sector i

X_{1i} = Cost of Production attributable to trucking after Infrastructure Investment for Industrial Sector i

e = Elasticity of output with respect to production cost (Currently set to -1)

$$X_{1i} = X_{0i}(1-\Delta\text{TC} \cdot a_i), \quad (\text{Equation 2-10})$$

where,

ΔTC = Percent change in trucking costs

a_i = Technical coefficient (relates the dollar value of TRUCK services required by an industry to produce a dollar of output)

Equations 2-9 and 2-10 are repeated for each industry sector (Table 2-7). The value generated by the difference between D_{0i} and D_{1i} is the value by which the I-O model is shocked for each industrial sector (Table 2-8). The I-O model is conducted as a single

Industry Change Activity with 20 Events occurring. It should be noted here that the operating cost reductions experienced by the transport by truck sector are the benefits experienced in the year calculated by the associated TDMs and discounted to a 2010 value. Unlike BCA, Economic Impact Analyses do not calculate NPV. Instead, the impact is expected to occur and change the state of the region's economy, putting it on an altered trajectory that can be assumed to be carried forward in time, all else being equal.

It should be observed that the values by which the I-O models are shocked (Table 2-7) do not add up to an equivalent number as that which is reported as the TDM Outputs (Tables 2-8a and 2-8b). This difference is a result of the operation of Equations 2-9 and 2-10, and dependent upon the given industries technical coefficients. In other words, the benefits experienced by the TRUCK sector (TDM Output) do not simply get divided equally among each user. Each freight-using sector experiences its own benefit based on its truck usage and does not take away from the benefit experienced by other sectors. The changes are all based on percent changes in costs of a productive input; transport by truck.

TABLE 2-7: Direct impact values used to ‘shock’ the I-O model. (D_{0i}-D_{1i}).

Sector	Output Difference (Direct Impact)			
	Project B		Project A	
	Region B	State	Region A	State
AGFOR	\$ 99,403	\$ 332,880	\$ 142,267	\$ 599,489
MIN	\$ 22,384	\$ 11,838	\$ 10,821	\$ 21,319
UTIL	\$ 34,608	\$ 11,186	\$ 12,683	\$ 20,146
CONST	\$ 814,596	\$ 891,195	\$ 1,903,838	\$ 1,604,970
MANUF	\$ 1,538,011	\$ 3,676,578	\$ 8,231,583	\$ 6,621,221
WTRAD	\$ 124,007	\$ 123,123	\$ 295,483	\$ 221,730
RTRAD	\$ 448,051	\$ 440,302	\$ 927,216	\$ 792,941
TRAWAR	\$ 60,858	\$ 103,532	\$ 284,331	\$ 186,449
TRUCK	\$ 394,358	\$ 393,869	\$ 709,479	\$ 709,368
INFO	\$ 50,992	\$ 216,427	\$ 701,978	\$ 389,759
FININS	\$ 35,449	\$ 28,964	\$ 67,010	\$ 52,161
REAL	\$ 46,310	\$ 64,485	\$ 147,809	\$ 116,130
PROTEC	\$ 58,235	\$ 110,303	\$ 283,016	\$ 198,642
MANAG	\$ 42,199	\$ 40,484	\$ 117,242	\$ 72,907
ADMIN	\$ 37,673	\$ 40,103	\$ 95,887	\$ 72,222
WMAN	\$ 11,048	\$ 37,069	\$ 44,170	\$ 66,757
SOCSER	\$ 366,592	\$ 278,242	\$ 598,448	\$ 501,083
ARTS	\$ 34,771	\$ 47,652	\$ 116,446	\$ 85,817
FOOD	\$ 150,378	\$ 165,760	\$ 355,526	\$ 298,516
OTHR	\$ 335,883	\$ 430,895	\$ 919,828	\$ 775,992
Total	\$ 4,705,806	\$ 7,444,887	\$ 15,965,060	\$ 13,407,618

TABLE 2-8a: Productivity Increases from Project B

TDM Output	\$ 4,533,563 ^a
Region B Intermediate Expenditures (TRUCK)	\$ 139,875,763
Statewide Intermediate Expenditures (TRUCK)	\$ 1,760,368,000
Change in Truck Transport Productivity (Δ TC) –Region B	3.24%
Change in Truck Transport Productivity (Δ TC) -State	0.26%

TABLE 2-8b: Productivity Increases from the SR-167 project

TDM Output	\$	8,164,392 ^a
Region A Intermediate Expenditures (TRUCK)	\$	869,913,300
Statewide Intermediate Expenditures (TRUCK)	\$	1,760,368,000
Change in Truck Transport Productivity(Δ TC) - Region A		0.94%
Change in Truck Transport Productivity (Δ TC) -State		0.46%

^a IMPLAN is all 2010 data, so the TDM model outputs are converted to 2010. Benefits include reduced operating costs and travel time savings. Emissions not included.

Implementing the Washington State CGE Model

Professors David Holland, Leroy Stodick and Stephan Devadoss developed a statewide regional CGE model that has been used extensively for evaluating economic impacts from a host of policy changes. These include applications ranging from statewide economic impacts from mad-cow disease to impacts from tariffs on Canadian softwoods and, more recently, for the legislative mandated “Biofuel Economics and Policy for Washington State” study completed in 2010. For a detailed description of this model, including model closure, specified import demand functions, export supply functions, factor demand functions and household demand functions, please see http://www.agribusiness-mgmt.wsu.edu/Holland_model/index.htm.

Here, we build four versions of the regional CGE; a statewide model and a county or counties level model for both case studies. For each case, we establish the models as a long-run (LR) evaluation in which capital and labor are mobile across sectors and the region-wide endowment is allowed to vary. The LR scenario depicts full realization of the benefits through the economy once it has had time – several years - to fully adjust. Short-Run (capital is fixed across industrial sectors and the total endowment for the

geographic region is also fixed) CGE models were also evaluated, though dropped in favor of the long-run model due to the nature of the projects in which the expectation is that an economic trajectory change is induced that should be permanently in place. The CGE model utilizes a set of equations and elasticities to reproduce the economy's inter-sector relationship in response to the produced counterfactual statements. Prior to introduction of the counterfactual, the models' parameters are calibrated such that it regenerates the original SAM. Example parameters used in calibration include various demand, substitution, and transformation elasticities.

Arguably, a transportation improvement project that reduces freight movement travel time and operating costs is in essence a technology improvement that permits the truck transportation industry to become more productive (increased efficiency) for a given level of capital and labor. These efficiencies are generally realized through reduced driver time on the road resulting in reduced labor costs; increased trip miles per unit of time per vehicle, resulting in more productive individual vehicles and thus requiring fewer trucks to accomplish the workload; and reduced vehicle repair and operating costs (FHWA, 2002). As such, each CGE model is initiated using the shift parameter for the industry's production function. This shift parameter, when adjusted, causes the industry supply curve to shift to the right or the left. The value assigned for the shift parameter is dependent upon the percent change in operating costs of the trucking industry (ΔTC). The percent change is dependent upon outputs of the travel demand model, the intermediate demand, and the selected regional coverage.

Regional Coverage

The model developed by Holland et al is a generic representation of Washington's economy, although one developed to closely represent how the state's economy functions and adheres to traditional neoclassical economic theory. Currently the model represents Washington State's economy, the rest of the U.S., and the rest of the World (only to the extent that Washington's economy interacts in these larger economies). However, by simply changing the region of consideration in IMPLAN, both the CGE and I-O models can be formulated to consider a subset of counties within Washington. Thus, in addition to comparing outputs between modeling frameworks, we also consider the effects of a changing geographic scale. For each of the two case studies, we construct the statewide models and sub-state models containing the county or counties (Identified as Region A or B) where the infrastructure improvement activity occurs and is related to the geographic scale of the TDMs.

Results: Regional Economic Impacts

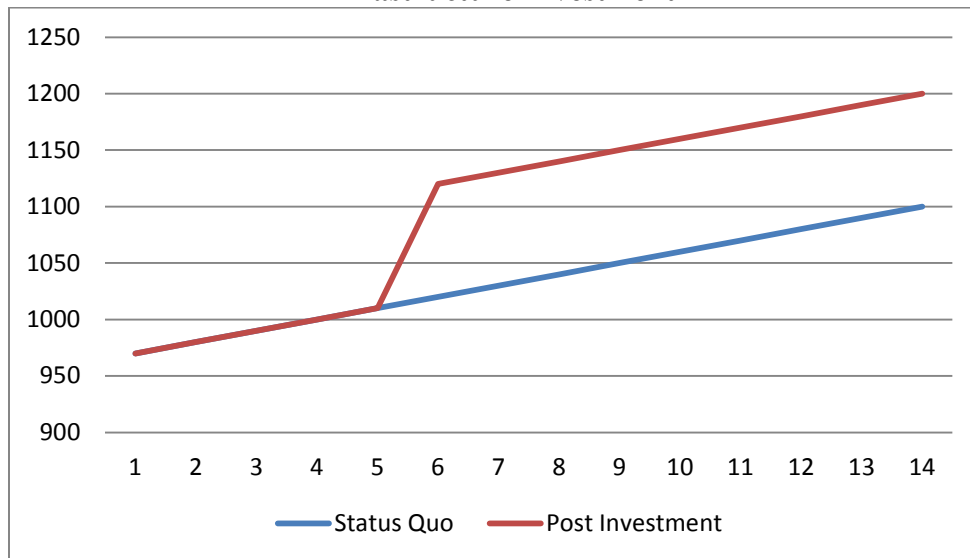
The resulting outputs and changes in employment are displayed in the tables below for the various operations described above. Both infrastructure improvement projects were evaluated at two geographic scales to better examine how the local economy variations impact model output. Both projects were examined at the state level (indicated as 'statewide' in the tables). Due to the nature of the evaluated projects, Project B was evaluated at the scale of a single county. Project A was evaluated at the scale of four counties. The four counties were selected due to their incorporation in the Region A TDM.

Though there are multiple ways to display the results of economic impact models, the most common and straightforward are in relation to changes in employment and regional output (this is the standard method of display in IMPLAN). It is important to note here that the recorded outputs in the tables below are not directly indicative of the quantity of activity occurring within the sector. The outputs are a measure of change of sales generated in the region by the sector. As such, the outputs displayed here are a function of the calculated price of the commodity in the sector and the quantity of activity. For instance, in all CGE models, the price of the transport by truck commodity is reduced and its activity quantity is increased; however, not all models generate an increased sale dollar amount. The interplay of price and quantity dictate the direction of sales output change.

- A job in IMPLAN = the annual average of monthly jobs in that industry (this is the same definition used by QCEW, BLS, and BEA nationally). Thus, 1 job lasting 12 months = 2 jobs lasting 6 months each = 3 jobs lasting 4 months each. A job can be either full-time or part-time. Information on converting between IMPLAN jobs and Full time equivalents can be found [here](#).
- Output represents the value of industry production. In IMPLAN these are annual production estimates for the year of the data set and are in producer prices. For manufacturers this would be sales plus/minus change in inventory. For service sectors production = sales. For Retail and wholesale trade, output = gross margin and not gross sales.

Infrastructure improvements such as those considered here provide a change in the state of the interactions of the factors within the economy. The change in state can be visualized as a step-up in the employment or output trend lines (Figure 2-5). The units of the figure are not included, as this is a generic representation of what may be expected. Thus, the changes in employment and output in the tables to follow represent the vertical value of the step and are characterized as the employment or output change in a single year. As this is not a forecasting model, we do not project the model forward. We only indicate that a change of state occurs and from that point forward, numerous factors influence the employment levels and industrial output.

FIGURE 2-5: Generalized Change in the State of the Economy Following Infrastructure Investment



Given the calculated output changes (direct impacts) resulting from the projects (Table 2-8) and the changes to trucking productivity (Table 2-8a, 2-8b), Tables 2-10 through 2-12 display the produced results for Project B, while Tables 2-13 through 2-15 display those for Project A. Interestingly, the results reveal that in all of the long-run CGE models, the

truck transport industry (TRUCK) has negative changes in employment numbers; job loss. At first glance, this may appear counterintuitive. However, these results can be thought about in relation to a cost of congestion study done previously in Washington State (Taylor, 2011). Taylor's survey and subsequent Input-Output modeling suggests that freight-dependent companies may respond to increased congestion (reduced productivity) by adding trucks (increasing employment). An opposite reaction is simulated here. In the present case, the TDMs suggest congestion relief stemming from the infrastructure improvement producing a positive effect, in that they simulate consumers increasing purchases of services and non-freight dependent goods (increased activity), as well as a negative effect that simulates the trucking industry's response of reducing employment.

In addition to the jobs modeled to be lost in the trucking sector, the sector associated with other transportation modes and warehousing (TRAWAR) also projects some, though markedly fewer, losses in each CGE model. Due to the aggregated nature of the sector, it cannot be directly determined which components of this sector are suggested to lose jobs; however, warehousing activity is the likely culprit given its intimate relationship with the transport-by-truck sector. Often, warehousing is aggregated with the transport by truck sector. Most of the sectors demonstrate only marginal changes in employment levels, with most experiencing less than a five job change. The information services sector is shown in three of the four CGE models to lose jobs, these numbers are low and likely an artifact of the model seeking equilibrium.

The sectors where job gains are substantial enough to take notice are found in several heavily freight dependent sectors. This is particularly true for the manufacturing sector in all models, as well as agriculture and forestry in the Region B and statewide models. These two sectors combined more than offset the losses experienced in the truck-transport sector. Other notable sector employment gains include retail trade gains resulting from Project A. Unlike manufacturing or agriculture and forestry, whose impacts are primarily direct effects, the impacts seen in relation to the social services sector are largely generated by induced effects.

It is important to preface the I-O model results by noting that the I-O will never produce a negative number when modeling an increase in output by a sector. This goes for the sectors directly impacted as well as all the indirect and induced effects. In essence (due to lack of information about the number of trucks added or reduced), we are only modeling one piece of the potential response. We see congestion relief from the project producing a positive effect in that it stimulates consumers to increase purchases of services and non-freight dependent goods (consumer benefit). The I-O model does not account for the trucking industry becoming more efficient and able to do more with fewer trucks. Given this, it is not surprising that in for three of the four models (only Region B differs), the I-O model results in higher job growth estimates. However, taking the output change under consideration, CGE models result in greater changes than their I-O counterparts. This observation is a result of the flexibility built into the CGE model through the counterfactual used that increases the productivity of the trucking sector for given levels of capital and labor. Additionally, the long-run scenario creates a more flexible system

that allows the allocation of both factors of production, capital and labor in an optimal manner.

The Region B model produces markedly different outcomes than do the other three models. As already stated, the CGE model in Region B produced employment gain numbers greater than the I-O and generated output changes more than three times that of the I-O; a substantially larger difference than the other models. These differences largely stem from the structure of the economy in the various regions of consideration. The structure of the economy, here, is meant to relate the relative size of the various sectors and their interrelationships with each other (e.g. the technical coefficients relating how much trucking services are purchased by the various sectors). Given the total size of the Region A economy in relation to the state as a whole, it is not surprising that the relationships between sectors are more similar than that of Region B.

PROJECT B

TABLE 2-9: Summary results (Project B)

		Employment	Output
Statewide Model			
LR-CGE	47.3		\$22,241,506
I-O	81.5		\$13,272,773
Region B Model			
LR-CGE	78.0		\$28,675,616
I-O	65.5		\$8,071,935

TABLE 2-10: Industry sector specific results in Region B from Project B

Sector	Employment Change		Output Change	
	LR-CGE	I-O	LR-CGE	I-O
AGFOR	14.5	2.1	\$ 810,244	\$ 122,594
MIN	0.2	0.1	\$ 116,766	\$ 47,671
UTIL	0.5	0.2	\$ 574,019	\$ 108,358
CONST	2.8	6.3	\$ 400,511	\$ 849,474
MANUF	45.8	5.6	\$13,676,449	\$1,732,818
WTRAD	5.6	2.2	\$ 1,281,445	\$ 325,035
RTRAD	9.6	10	\$ 1,070,359	\$ 690,476
TRAWAR	-2.6	1.2	\$ 125,054	\$ 148,070
TRUCK	-38.0	4.1	\$ (179,227)	\$ 463,447
INFO	0.8	0.6	\$ 338,942	\$ 154,072
FININS	1.6	2.6	\$ 1,658,911	\$ 564,862
REAL	3.1	2	\$ 2,032,816	\$ 579,957
PROTEC	5.0	3.1	\$ 1,123,688	\$ 292,864
MANAG	4.1	0.8	\$ 852,326	\$ 143,644
ADMIN	6.5	2.6	\$ 579,023	\$ 149,181
WMAN	0.2	0.1	\$ 89,747	\$ 22,833
SOCSE	2.5	7.9	\$ 1,661,203	\$ 724,719
ARTS	2.1	1.7	\$ 129,897	\$ 67,695
FOOD	5.8	4.7	\$ 532,115	\$ 277,366
OTHR	7.8	7.6	\$ 1,801,328	\$ 606,799
Total	78.0	65.5	\$28,675,616	\$8,071,935

TABLE 2-11: Industry sector specific results statewide from Project B

Sector	Employment Change		Output Change	
	LR-CGE	I-O	LR-CGE	I-O
AGFOR	13.7	4.6	\$ 1,353,582	\$479,343
MIN	0.4	0.1	\$ 91,114	\$30,208
UTIL	0.3	0.1	\$ 338,505	\$65,987
CONST	2.5	6.4	\$ 165,292	\$939,173
MANUF	27.0	9.9	\$11,510,000	\$4,668,419
WTRAD	2.9	2.7	\$ 749,878	\$447,570
RTRAD	6.8	10.9	\$ 631,774	\$792,796
TRAWAR	-3.2	1.7	\$ 166,450	\$264,503
TRUCK	-32.8	4	\$ 80,113	\$479,240
INFO	-0.9	1.1	\$ 214,267	\$548,862
FININS	2.5	3	\$ 1,030,947	\$660,760
REAL	2.4	3	\$ 1,497,725	\$890,036
PROTEC	2.3	4	\$ 763,024	\$475,012
MANAG	1.7	1	\$ 410,089	\$198,876
ADMIN	3.4	3	\$ 350,103	\$195,586
WMAN	0.1	0.2	\$ 60,675	\$66,798
SOCSER	6.8	8.3	\$ 1,165,260	\$755,616
ARTS	1.3	2.1	\$ 98,533	\$102,694
FOOD	3.8	5.7	\$ 294,753	\$343,971
OTHR	6.2	9.7	\$ 1,269,422	\$867,323
Total	47.3	81.5	\$22,241,506	\$13,272,773

PROJECT A

TABLE 2-12: Summary results (Project A)

	Employment	Output
Statewide Model		
LR-CGE	85.1	\$40,032,564
I-O	147.0	\$23,903,155
Region A Model		
LR-CGE	55.5	\$34,797,920
I-O	135.9	\$23,163,908

TABLE 2-13: Industry sector specific results in Region A from Project A

Sector	Employment Change		Output Change	
	LR-CGE	I-O	LR-CGE	I-O
AGFOR	2.6	0.9	\$ 458,833	\$ 162,220
MIN	0.5	0.1	\$ 81,161	\$ 24,809
UTIL	0.2	0.1	\$ 282,394	\$ 82,423
CONST	3.5	11.2	\$ (220,120)	\$ 1,765,154
MANUF	65.8	16	\$26,940,775	\$ 7,287,183
WTRAD	4.9	4.6	\$ 1,217,588	\$ 828,811
RTRAD	11.8	18.1	\$ 856,045	\$ 1,421,375
TRAWAR	-22.5	3.6	\$ (1,972,232)	\$ 619,333
TRUCK	-52.3	6.6	\$ (443,142)	\$ 846,983
INFO	-6.2	2.6	\$ (1,770,518)	\$ 1,449,344
FININS	4.1	5.6	\$ 1,576,007	\$ 1,266,748
REAL	2.9	5.4	\$ 1,846,269	\$ 1,582,808
PROTEC	2.3	7.4	\$ 865,956	\$ 987,127
MANAG	5.2	2.2	\$ 1,188,807	\$ 455,877
ADMIN	2.7	5.6	\$ 382,313	\$ 412,955
WMAN	0.2	0.3	\$ 63,573	\$ 84,163
SOCSER	12.4	15.2	\$ 1,538,130	\$ 1,466,137
ARTS	2.3	4.2	\$ 124,164	\$ 219,494
FOOD	5.9	10.3	\$ 321,379	\$ 649,390
OTHR	9.2	15.9	\$ 1,460,538	\$ 1,551,574
Total	55.5	135.9	\$34,797,920	\$23,163,908

TABLE 2-14: Industry sector specific results statewide from Project A

Sector	Employment Change		Output Change	
	LR-CGE	I-O	LR-CGE	I-O
AGFOR	24.7	8.3	\$ 2,434,388	\$863,258
MIN	0.7	0.2	\$ 163,883	\$54,401
UTIL	0.6	0.2	\$ 609,093	\$118,837
CONST	4.4	11.6	\$ 297,974	\$1,691,373
MANUF	48.5	17.8	\$20,710,000	\$8,407,446
WTRAD	5.3	4.8	\$ 1,349,171	\$806,033
RTRAD	12.2	19.7	\$ 1,137,063	\$1,427,753
TRAWAR	-5.7	3.1	\$ 301,464	\$476,347
TRUCK	-58.9	7.3	\$ 150,264	\$863,115
INFO	-1.6	2	\$ 387,011	\$988,445
FININS	4.5	5.4	\$ 1,855,827	\$1,189,973
REAL	4.2	5.4	\$ 2,695,406	\$1,602,876
PROTEC	4.1	7.1	\$ 1,373,595	\$855,452
MANAG	3.1	1.8	\$ 737,807	\$358,158
ADMIN	6.2	5.4	\$ 630,411	\$352,234
WMAN	0.1	0.4	\$ 109,365	\$120,297
SOCSER	12.3	15	\$ 2,097,184	\$1,360,793
ARTS	2.3	3.8	\$ 177,371	\$184,943
FOOD	6.9	10.3	\$ 530,516	\$619,458
OTHR	11.1	17.4	\$ 2,284,771	\$1,561,963
Total	85.1	147	\$40,032,564	\$23,903,155

Discussion and Recommendations

Infrastructure improvement projects that reduce operating costs and travel time of freight users on the roadway is an activity that inherently affects the **productivity and economic efficiency** of the user; two critical components that are addressed in the National Freight Policy provisions of MAP-21. As readily available and user friendly as I-O models are, their major drawback is the inability to simulate a change in productivity directly. To assess the economic impacts of such infrastructure improvement projects, the benefits experienced by the users must be manually translated into a change in demand by freight users. The preceding sections detail the methods by which this conversion may be accomplished. Despite being able to compute the change in demand, the I-O model described here is not able to fully account for the improved productivity of the trucking industry, and thus cannot confidently model how the trucking sector meets the increased demand.

Where infrastructure projects are large enough and productivity is increased to the point that now fewer trucks – and therefore fewer drivers – can meet the demand needs, we may experience a reduction in employment in the transport-by-truck sector. The I-O model does not pick this up. However, the CGE is able to directly model increased productivity of an industry and are thus able to model the entire economy-wide reaction to the infrastructure improvement that is a result of decreased operating cost and travel time. It is for this specific ability to model productivity changes that a regional CGE model should be incorporated into the prioritization process as an aside to the BCA described in the first section of this report. Together, these analyses will better inform

agency prioritization decisions with regard to the affect infrastructure projects have on freight systems and the economy that is necessarily interwoven with them. As more benefits accrue and are accounted for, the impact on the economy will continue to grow. Thus, as capabilities to account for benefits stemming from increases in reliability are developed, a more complete impact can be assessed.

Appendix 2-1

Comparison of the transportation related benefits estimated by Analyst 1, Analyst 2, and UW/WSU (unit: millions of dollars).

	Analyst 1 Study	Analyst 2 Study	UW/WSU Study
Truck Benefits (2020-2041)	\$143 (2021-2041)^a	\$82	\$83^b
Benefits	Travel time Reliability Operating cost Toll cost	Travel time Reliability Operating cost Toll cost	Travel time Operating cost Emissions
Project description	Building three lanes in each direction for a segment, and two lanes in each direction for another. Five interchanges throughout the project	Building one lane in each direction for a segment, and two lanes in each direction another. Partial interchanges at four locations.	Building one lane in each direction for two segments. Building two lanes in each direction for another segment. Partial interchanges at five locations.
Benefit details (millions of dollars)	Analysis period: 2021-2050 Passenger vehicles: \$1,707 (84.3 percent) Light commercial: \$220 (10.9 percent) Medium truck: \$47 (2.3 percent) Heavy truck: \$21 (1.5 percent) Total truck benefits: \$288	Analysis period: 2020-2040 Travel time saving: \$362 Reliability benefits: \$0.4 Truck operating cost saving: \$135 Toll cost Savings: \$145 Total truck benefits: \$82	Analysis period: 2020-2040 Change in truck VHT (daily): 526 hours Travel time saving: \$30.5 Truck operating cost saving: \$50.4 Emission improvement: \$1.8 Total truck benefits: \$83

Significant differences between the studies:

^a Cambridge report documented the total benefits over the analysis period 2021-2050. To compare the results, it was necessary to ensure that, to the extent possible, the benefits in each case reflect the same time period. We modified the results presented to reflect the benefits from 2021 to 2040. This result was calculated assuming the annual benefits increase at a constant rate equal to the 2050 benefits divided by number of analysis years between 2021 and 2050 (30 years).

^b The daily benefits are converted to annual benefits using the parameter of 300 days/year, the same as PSRC study.

(1) The project studied by Analyst 1 is different from the UW/WSU and Analyst 2 as described under “Project description” in the table above. The project analyzed by Analyst 1 is expected to generate larger benefits than the other projects due to larger scale of its proposed project.

(2) The benefits considered are different in each study. Analysts 1 and 2 analyzed the changes in travel time, reliability, operating cost and toll cost, while the UW/WSU team analyzed the impacts on travel time, operating cost and truck emissions.

CHAPTER III

Methodological Development of the Utilization of GPS in Estimating Travel Time and Travel Time Reliability

Truck travel time measures based on GPS data have been examined in previous research efforts (refer to Chapter I). In addition to those previously discussed, Zhao et al. (2011) compared two algorithms, the *space mean speed*-based and *spot speed*-based methodologies.

The *space-mean speed* method estimates the truck travel speed by creating two buffers with radius of 1 mile each at the segment start and end points to capture the GPS reads near the two points. The truck trips recorded near both the start and end points are identified, and the corresponding travel distance and travel time are computed by comparing the GPS reads mileage and time stamp information respectively. From the *space-mean speed*, the travel time along links can then be computed.

In the implementation of the *spot-speed* method, the mean of GPS spot speed is viewed as the average speed along the segment, and the travel time is calculated based on the mean spot speed. The major limitation of this method is that the *spot speed* cannot represent the real speed along the segment if the segment is too long, and some bottlenecks along the segment may be neglected.

The *space-mean speed* is able to estimate more realistic travel time estimates, but requires statistically sufficient observations of trips recorded at both segment start and end points. Our current data may not be able to provide enough observations to support the space-mean method as the data was initially collected for commercial vehicle operation and the reading frequency ranges from 2 to 60 minutes. By comparing the

results estimated using the two methods, it is found that the travel time estimates computed by the two algorithms are very close and the mean absolute difference is less than 6 percent. Since the results of the two methods are comparable, we recommend using the estimated *spot-speed method* to calculate truck travel time.

The following sections detailed the three phased approach taken to first establish a methodology to be used to estimate travel time and travel time reliability from GPS data, followed by a case study implementation of the reviewed methods. We conclude with a section investigating methods that can be used to estimate future travel time and travel time reliability using current performance as measured by GPS data.

Establishing a GPS Based Reliability Methodology

Travel time reliability represents the variation in travel time and, given the value the freight world places on reliability, it has been proposed as a relatively new concept to support agencies in evaluating facility performance. Its measurement is based on day-to-day and/or across different time periods of the day observations. As a critical indicator of freight system performance, there has been substantial effort to develop travel time reliability measures relying upon statistically valid techniques. Through careful consideration of many proposed techniques, three measures have been selected and are discussed in the following paragraphs as they are:

- **Measureable and implementable with our current GPS data;**
- **Reasonably accurate;**
- **Can be applied in the benefit-cost analysis process;**
- **Represent information in addition to the mean travel time.**

Each of the four characteristics above have been identified as valuable considerations for implementation into an active evaluation systems by various departments of transportation.

Travel Time Standard Deviation

In the context of travel time, the standard deviation is a measure of the spread of observed time taken to traverse the specified distance. The larger the value of the standard deviation, the lower travel time reliability. In other words, as the standard deviation increases, the ability to reliably gauge the length of time a trip will take decreases. In addition to the standard deviation, the ratio of standard deviation and the mean was defined as reliability measure. The larger the size of the standard deviation from the mean, the lower travel time reliability.

$$S = \sqrt{\frac{\sum_{i=0}^N (X_i - \bar{X})^2}{N-1}} , \quad \text{Equation (3-1)}$$

where:

S = travel time standard deviation

X_i = i^{th} travel time observation

\bar{X} = average travel time

N = number of observations

$$\text{standard deviation} \sim \text{mean ratio} = \frac{S}{X} \quad \text{Equation (3-2)}$$

The major limitation of using travel time standard deviation is that it does not provide travelers with straight forward information regarding the estimated travel time between given origin-destination pairs (O-D's), or extra travel time that travelers need to plan for to ensure on time arrival. It is not an easily translatable metric for the common user.

Additionally, the travel time standard deviation method treats the late and early arrival in the same fashion. In the trucking industry, among other commerce based industries, this lack of differentiation is significant, where the late arrival accrue more penalties, and routinely delayed arrivals may inhibit future contract opportunities and value. However, it presents how spread the data is, and can be used to estimate other reliability metrics, namely those based on percentiles such as that of the 95th percentile travel time, if the travel time distribution is known.

Percentiles

95th Percentile Travel Time

The 95th percent travel time method is used to measure how bad the traffic would be based on observations over certain time period (e.g. one year). In another words, it estimates the time travelers need to plan for in order to accomplish their trips on time. It is also called planning time. It is recommended by National Cooperative Highway Research Program (NCHRP) as the simplest indicator of travel time reliability (NCHRP-618, 2008).

Buffer Time and Buffer Time Index

Buffer time is defined as the extra travel time travelers must add to the average travel time to allow for on-time arrival, and it is calculated as the difference between the 95% travel time and average travel time as shown in equation 3-3 (USDOT 2006a). The buffer time index is calculated by dividing buffer time by the average travel time. The calculation is presented in equation 3-4.

$$\text{Buffer time} = 95 \text{ percent travel time} - \text{Average travel time} \quad \text{Equation (3-3)}$$

$$\text{Buffer time index} = \frac{95 \text{ percent travel time} - \text{Average travel time}}{\text{Average travel time}} \times 100\% \quad \text{Equation (3-4)}$$

Planning Time and Planning Time Index

Planning time is the travel time needed to plan to ensure on-time arrival, and is equal to the 95th percentile travel time. The planning time index represents the total travel time a traveler should plan for to ensure on-time arrival 95% of the time relative to the free flow travel time and it is computed as the 95th percentile of travel time divided by free-flow travel time as shown in equation 3-5 (USDOT 2006a).

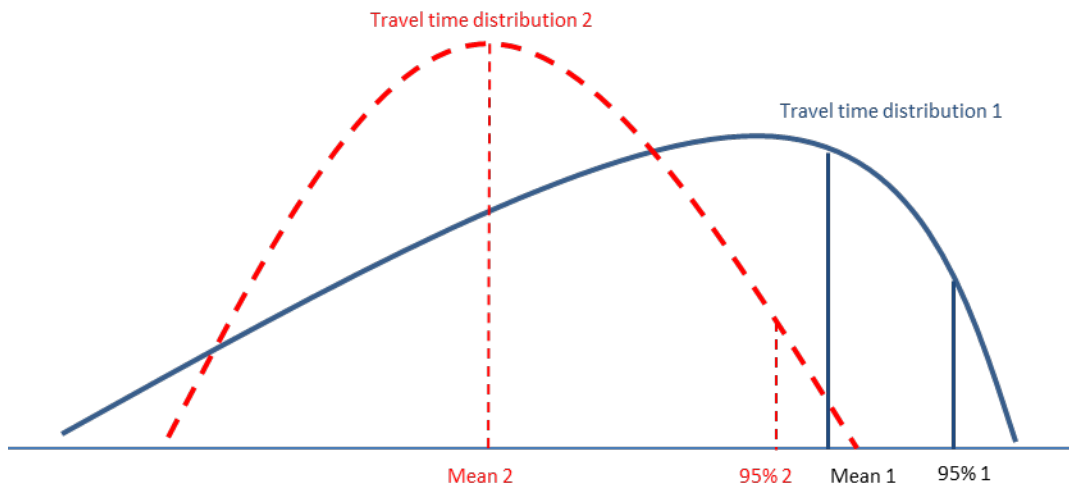
$$\text{Planning time index} = \frac{95 \text{ percent travel time}}{\text{Free flow travel time}} \times 100\% \quad \text{Equation (3-5)}$$

It should be noted that the smaller values of buffer time and planning time do not necessarily represent better reliability. For instance, adding capacity to current roadway is expected to reduce travel time and improve travel time reliability as shown in Figure 3-

1. According to Figure 3-1, the travel time distribution curve changed from right-skewed to normal distribution, and both the average travel time and reliability are improved. However, the buffer index may be greater due to the reduction in travel time according to equation 3-3.

In addition, these travel time distribution methods require adequate daily observations, and it is challenging while using low reading frequency GPS data. What's more, at this time, we haven't found any nationally accepted minimum sample size calculation method.

FIGURE 3-1: Change in Travel Time Distributions due to Roadway Capacity Increasing



Bimodal Method

The measures discussed in the above sections rely upon considerable travel time observations retrieved from loop detectors or truck GPS devices. Two of the major challenges of using GPS data in practice, for travel time reliability calculations, are the

low number of observations in areas with low truck traffic volume, and low GPS reading frequency (Harrison and Shofield, 2007). The bimodal method discussed below uses the GPS spot speed instead of travel time data retrieved from raw spot speed data, which provides a reliability measure with sparse dataset.

WSDOT has evaluated the truck reliability performance and identified freight bottlenecks using GPS sample data collected since 2008 (Zhao et al., 2013). The data represents approximately 3 percent of total trucks traveling in Washington State. The probe data is sparse on most segments, and are not sufficient to provide a daily travel time distribution to support travel time reliability analyses using the methods discussed in the previous sections. Instead of examining the travel time distribution, the WSDOT plots the spot speed on each segment during certain time periods, and assesses the reliability by evaluating the speed distributions with the assumption that the travel time is unreliable if bimodal distributions are observed, and otherwise (unimodal distribution) it is reliable. Zhao et al. (2013) demonstrated that travel speed best follows a mixture of two normal distributions as traffic is composed of two stages: free-flow condition and congestion condition. Truck spot speed distribution is represented by five parameters, including the mean (μ_1) and standard deviation (σ_1) of the congested speed distribution, the mean (μ_2) and standard deviation (σ_2) of the free-flow speed (V_f) distribution, and the proportion of the two distributions (α). The probability density function of a mixture of two Gaussian distribution is shown in Equation 3-6. The parameters are fitted based on the maximum likelihood rule.

$$f(x) = \alpha \cdot n(x, \mu_1, \sigma_1) + (1 - \alpha) \cdot n(x, \mu_2, \sigma_2)$$

$$n(x, \mu_i, \sigma_i) = \frac{1}{\sqrt{2\pi\sigma_i^2}} \cdot \exp\left[-\frac{(x - \mu_i)^2}{2\sigma_i^2}\right]$$

Equation (3-6)

The approach defines the travel condition as unreliable *iff*:

- $|\mu_1 - \mu_2| \geq |\sigma_1 + \sigma_2|$,
- $\alpha \geq 0.2$, and
- $\mu_1 \leq 0.75 * V_f$,

otherwise it is viewed as reliable (*Note: All three conditions must be met to be considered unreliable*). Performance deemed reliable is subdivided into reliably fast and reliably slow depending on the average speed. If traffic along the segment is defined as reliable and $\mu_1 \leq 0.75 \times V_f$, then the traffic is reliably slow, otherwise it is reliably fast. Truck reliability serves as one indicator for ranking freight bottlenecks in Washington State. The major advantage of this methodology is that the reliability evaluation does not require extensive daily observations of travel time, but only spot speed, which is easier to obtain from current GPS data. However, the current method does not provide an actual number, or index, to reflect the segment reliability, but only a category used to classify the reliability as reliable fast, reliable slow and unreliable.

Case Studies

Two case studies were tested and presented in this document. The first one is a 10-mile long I-90 segment located near Spokane. The second one is a 3.5-mile long I-5 segment

passing through Downtown Seattle. According to the results, the traffic conditions along each segment are significantly different: traffic on I-90 is reliable even during AM peak period, and traffic on I-5 is severely congested during AM peak period and reliable during night period. Both segments are evaluated using the three identified reliability metrics to examine the comparability of all three methods under different traffic conditions and locations.

Case Study I

Study area: Eastbound (EB) I-90 between N Sullivan Rd and Idaho State Line

Length: 9.95 mile

Data: GPS data was collected in June 2012.

Analysis period: weekday AM Peak (6 AM -9 AM)

Results

The average travel speed and travel time estimates along the segment are shown in Table 3-1. Reliability measurements are presented in Table 3-2.

TABLE 3-1: Average Truck Travel Speed and Travel Time

Date	Average speed (mph)	Average travel time (minute)
6/1/2012	62.980	9.483
6/4/2012	63.075	9.482
6/5/2012	63.468	9.425
6/6/2012	57.802	10.691
6/7/2012	62.509	9.584
6/8/2012	62.218	9.617
6/11/2012	62.533	9.565
6/12/2012	64.572	9.267
6/13/2012	63.786	9.397
6/14/2012	63.085	9.470
6/18/2012	61.054	9.780
6/19/2012	62.496	9.558
6/20/2012	63.177	9.473
6/21/2012	62.229	9.595
6/22/2012	64.018	9.342
6/25/2012	62.488	9.628
6/26/2012	64.172	9.315
6/27/2012	64.765	9.240
6/28/2012	63.499	9.411
6/29/2012	64.668	9.266

TABLE 3-2: Travel Time Reliability Analysis Results

Method	Measures	
	Mean speed (mph)	62.930
	Mean travel time (min)	9.530
Standard deviation method	Standard deviation (min)	0.307
95th percentile travel time method	95% travel time (min)	10.645
	Buffer time (min)	1.116
	Buffer time index	11.710%
	Planning time index (<i>i</i>)	1.159
Bimodal method	Bimodal method	Reliably fast

i - Free flow speed was assumed to be 60 mph.

The fitted travel speed distribution using the bimodal approach is shown in Figure 3-2.

The five parameters were estimated based on the estimation maximization (EM)

algorithm using R software and are presented in Table 3-3.

FIGURE 3-2: EB I-5 Travel Speed Distribution during AM peak period Fitted using a Mixture of Two Normal Distributions

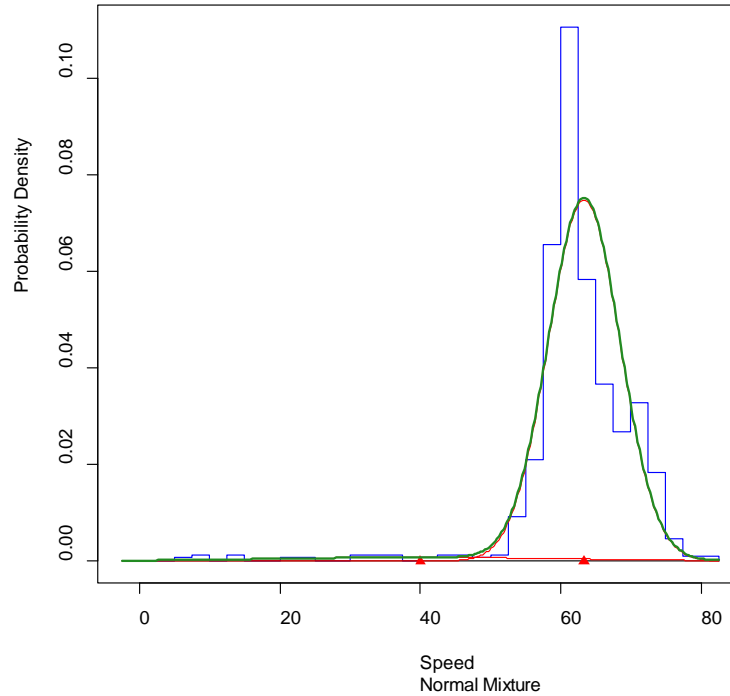


TABLE 3-3: Estimated Parameters for Speed Distribution

Parameter	α	μ_1	σ_1	μ_2	σ_2
Value	0.041	40.046	21.600	63.357	5.107

Since $|\mu_1 - \mu_2| = 23.311 < |\sigma_1 + \sigma_2| = 26.707$, the travel time is defined as reliable.

Meanwhile, *average speed* = 62.93 > 0.75 × V_f (V_f is free flow, or posted speed), so the travel time is defined as reliably fast.

Case Study II

Study area: Southbound (SB) I-5 between SR-520 and I-90

Length: 3.47 mile

Data: GPS data was collected in May 2012.

Analysis period: Weekday Night (12 AM – 6 AM) and AM Peak (6 AM -9 AM)

Results

TABLE 3-4: Comparison of the three methods

Methods	Measures	Night (12 AM – 6 AM)	AM Peak (6 AM – 9 AM)
	Mean speed (mph)	57.324	38.831
	Mean travel time (min)	3.638	5.618
Standard deviation method	Travel time standard deviation (min)	0.027	1.325
95th percentile method	95 th percentile travel time (min)	3.932	8.990
	Buffer time (min)	0.294	3.371
	Buffer time index (%)	8.1%	60.0%
	Planning time index (ii)	1.133	2.591
Bimodal method	Bi-modal method evaluation results	Reliably fast	Unreliable

ii - Free flow speed was assumed to be 60 mph.

FIGURE 3-3: SB I-5 Travel Speed Distribution during Night and AM peak period Fitted using a Mixture of Two Normal Distributions

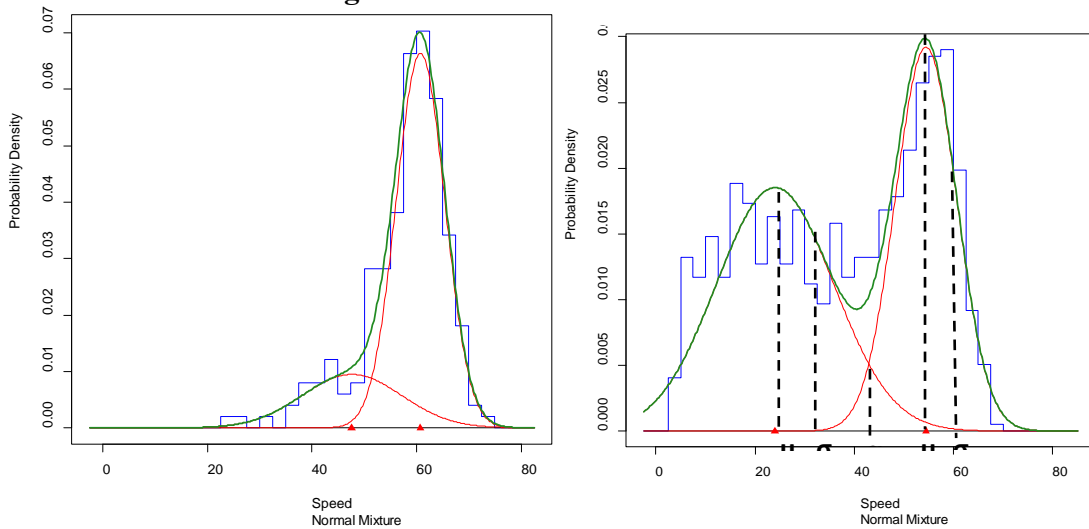


TABLE 3-5: Results of the Bimodal Approach

Parameter	Night (12 AM – 6 AM)	AM Peak (6 AM – 9 AM)
μ_1	47.641	24.011
σ_1	9.512	11.780
μ_2	60.763	54.437
σ_2	4.652	6.189
α	0.226	0.547
If $ \mu_1 - \mu_2 \geq \sigma_1 + \sigma_2 $	No	Yes

Discussion

The comparison of the three methods for Case Study I is shown in Table 3-2, and for Case Study II is presented in Table 3-4. According to Table 3-2, the results produced by the three methods are comparable, and all suggest that the truck travel time along the I-90 segment evaluated is reliably fast during AM peak period. Similarly, results presented in Table 3-4 indicate that results are comparable, and the I-5 segment evaluated in the case study is, as could be expected, reliably fast during the night period and unreliable during AM peak period.

To increase the utility of the bimodal method developed and evaluated in the case studies discussed above, extensions should, and can readily be made. Such an extension has been performed by Zhao et al. (2013). In their analysis, which is tangent to this report, the authors identify a means of ranking the results of the bimodal analysis in such a fashion as to be able to identify the worst bottlenecks on an agency's (WSDOT in the present case) roadway network. Using the three travel conditions previously identified: (1) unreliable, (2) reliably slow, or (3) reliably fast, the authors produced a tiered set of ranking system rules. Identification begins with the selection of those segments in which

at least one time period is unreliable or reliably slow. Those segments making this cut are then classified based on the frequency in which congestion exceeds an established threshold. Priority is then based on the highest frequency of congested travel. The placement of reliability as the first filter suggests the importance placed on it by both the trucking industry and state DOTs.

Estimation of Future Truck Travel Time

The pre-investment truck travel time and travel time reliability can be calculated based on the truck GPS observations collected over years. However, what those observations do not reveal, are the post-investment travel time and travel time reliability on the addressed segment. This final section discusses the methodologies for the development of predict estimates of those parameters.

Highway Capacity Manual Method (HCM 2000)

The *HCM 2000* (TRB, 2000) proposes equations for estimating the vehicle speed and travel time along different facility types, including freeway, arterial and rural highway systems. These equations do not separately consider the truck specific travel speed, but rather general traffic. The infusion of trucks to the HCM methodology is found in its consideration of the fact that trucks occupy more roadway space while estimating the facility capacity.

For instance, the capacity of freeway system is estimated as:

$$c = Q * N * f_{HV} * f_p * PHF, \quad \text{Equation (3-7)}$$

where:

c = capacity (veh/h)

Q = PCE capacity (pc/h/ln)

N = number of through lanes (ignoring auxiliary and exit only lanes)

f_{HV} = heavy-vehicle adjustment factor,

f_p = driver population adjustment factor, and

PHF = peak hour factor

$$f_{HV} = \frac{1}{1 + P_T(E_T - 1) + P_R(E_R - 1)}$$

where:

P_T = proportion of trucks in the traffic stream, expressed as a decimal

P_R = proportion of RVs in the traffic stream, expressed as a decimal

E_T = passenger-car equivalent for trucks

E_R = passenger-car equivalents for RVs

and the link-level travel time for general traffic is estimated according to the equation below:

$$R = R_0 + D_0 + 0.25T \left[(X - 1) + \sqrt{(X - 1)^2 + \frac{16J * X * L^2}{T^2}} \right], \quad \text{Equation (3-8)}$$

where,

R = link traversal time (h)

R₀ = link traversal time at link free flow speed (FFS) (h)

D₀ = zero-flow control delay at signalized intersection (h)

T = expected duration of demand (typically 1h) (h)

X = link demand to capacity ratio

L = link length (mi), and

J = calibration parameter

$$J = \frac{(R_c - R_0)^2}{L^2}$$

The free flow travel time can be estimated using the GPS data. The FAF³ provides important information on national and state freight commodity flow estimates and truck performance measurements (FHWA, 2011). The truck travel time estimates were

estimated using the same methodology proposed in the *HCM 2000* (equation 3-7 and equation 3-8).

BPR (Bureau of Public Roads) Function

The BPR function proposed equations for estimating travel time along different facility types, including freeway and multilane highways, and arterials. Link travel time is mainly estimated by free-flow travel time, volume-capacity ratio and corresponding parameters determined by facility type. The facility capacity is estimated using the same HCM methodology (equation 7). Equation 3-9 presents the BPR function (TRB, 2000).

$$R = R_0 \left[1 + a \left(\frac{v}{c} \right)^b \right], \quad \text{Equation (3-9)}$$

where:

a and b = BPR parameters

Facility Type	Free-Flow Speed (mi/h)	Speed at Capacity (mi/h)	a	b
Freeway	75	53	0.39	6.3
	70	53	0.32	7.0
	65	52	0.25	9.0
	60	51	0.18	8.5
	55	50	0.10	10.0
Multilane highway	60	55	0.09	6.0
	55	51	0.08	6.0
	50	47	0.07	6.0
	45	42	0.07	6.0

Arterial Class	Free-Flow Speed (mi/h)	Signal Spacing (signals/mi)	Speed at Capacity (mi/h)	a	b
Class I	50	0.2	33	0.34	4.0
	50	1.6	19	0.74	5.0
	50	4.0	9	1.16	6.0
Class II	40	0.8	25	0.38	5.0
	40	1.6	17	0.70	5.0
	40	3.2	11	1.00	5.0
Class III	35	3.2	11	0.96	5.0
	35	4.8	8	1.00	5.0
	35	6.4	6	1.40	5.0
Class IV	30	6.4	6	1.11	5.0
	30	8.0	5	1.20	5.0
	30	9.7	4	1.50	5.0

The above equations (3-7, 3-8, and 3-9) for estimating travel time are based on national average conditions. In application, an analyst should verify and customize these equations and their parameters with local data. If the travel time observations obtained from field data are within an acceptable range of the estimated travel time estimates, the above equations can be viewed to be verified against local conditions. Otherwise, further calibration with field data is needed. Our GPS dataset can be used to calibrate these equations.

Estimation of Future Truck Travel Time Reliability

The reliability of travel time can be evaluated by different measures, (e.g. travel time variance, 95th percentile travel time, buffer time, and planning time index). The travel time variance can be estimated based on the changes in segment capacity (equation 3-10 and 3-11 below). Other reliability metrics, buffer time and 95th percentile travel time, can be calculated from the travel time variance data.

Travel Time Variance Forecasting

The NCHRP Report 618 proposed method to compute travel time reliability based on the variability of segment volume-capacity ratio (V/C). Since travel time is defined as a function of volume-capacity ratio (V/C), the travel time variance is a function of V/C variance, as shown in equation 3-10.

For $v/c \leq 1.00$ Equation (3-10)

$$Var(T) = a^2 * Var(v/c)$$

For $v/c > 1.00$

$$Var(T) = b^2 * Var(v/c)$$

where:

T = predicted travel time (h)

T₀ = Free-Flow travel time (h)

a = Calibration parameter = T_c-T₀

b = 0.25 (average delay per deterministic queuing theory)

T_c = Travel time and capacity (h)

HCM Facility Type	Free-Flow Speed (MPH)	Speed at Capacity (MPH)	Free-Flow Travel-Time Rate (T ₀) (Hours/Miles)	Capacity Travel-Time Rate (T _C) (Hours/Mile)	Calibration Parameter a=T _C -T ₀ (Hours/Mile)
Freeway	75	53.3	0.0133	0.0188	0.0054
	70	53.3	0.0143	0.0188	0.0045
	65	52.2	0.0154	0.0192	0.0038
	60	51.1	0.0167	0.0196	0.0029
	55	50.0	0.0182	0.0200	0.0018
Multilane Highway	60	55.0	0.0167	0.0182	0.0015
	55	51.2	0.0182	0.0195	0.0013
	50	47.5	0.0200	0.0211	0.0011
	45	42.2	0.0222	0.0237	0.0015
Arterial	50	20.0	0.0200	0.0500	0.0300
	40	17.0	0.0250	0.0588	0.0338
	35	9.0	0.0286	0.1111	0.0825
	30	7.0	0.0333	0.1429	0.1095
Two-Lane Highways	55	40.0	0.0182	0.0250	0.0068

- Sources:
1. Freeways: Exhibit 23-2 HCM.
2. Multilane Highways: Exhibit 21-2 HCM.
3. Arterials: HCM Exhibits 15-8, 15-9, 15-10, 15-11, Middle Curve.
4. Two-lane Highways: Exhibit 20-2, HCM.

The variance of v/c can be calculated as

$$Var(v/c) = E(v^2) * E(1/c^2) - [E(v)]^2 * [E(1/c)]^2 \quad \text{Equation (3-11)}$$

The expected value of the inverse v/c can be computed using the following equations:

$$E\left(\frac{1}{C}\right) = \sum_{i=1}^N P(x_i) * \frac{1}{C_0 - x_i} \quad 0 \leq x_i < C_0$$

$$E\left(\frac{1}{C^2}\right) = \sum_{i=1}^N P(x_i) * \frac{1}{C_0 - x_i^2} \quad 0 \leq x_i < C_0$$

$$P(x = a_i * C_0) = \frac{\frac{Events * Hours}{Year * Event}}{\frac{Hours}{Year}} \quad \text{Equation (3-12)}$$

The future travel time reliability (travel time variance) can be predicted based on equations 3-10 to 3-12. Since the mean and variance of travel time can be estimated, the reliability can be calculated using the buffer time index metric as well. Assuming the travel time follows a Gamma distribution, the buffer index can be calculated as shown in equation 3-13. The mean value of travel time is forecasted based on equations 3-7, 3-8 or 3-9. The GPS data is employed to estimate the average travel time, and consequently travel time variance.

$$BI = \left[3.0 * \frac{Var(T)}{Mean(T)^2} - 1 \right] * 100\% \quad \text{Equation (3-13)}$$

It should be noted that there are two types of unreliability, (1) caused by infrastructure design, e.g. lane width and slope (terrain), and (2) caused by traffic congestion. The truck travel speed under the first situation is always slower than the free-flow speed, but the speed over time is stable, which is viewed as a reliably slow condition. Speed under congestion condition is slower than the free-flow speed as well, but fluctuates more over time, which is viewed as an unreliable condition. These two situations should be analyzed separately while evaluating reliability.

Travel Time Reliability Measures Recommendations

The selection of proper reliability measures for benefit-cost analysis project includes the evaluation of data availability and the estimation of post-project freight reliability.

De Jong et al. (2004b) argue that the prediction of departing or arriving earlier or later than necessary departure or arrival time is the most relevant for valuing freight travel time reliability but unfortunately requires a level of detail not available for most researchers or agency personnel. In particular, it requires information on scheduled, desired, and actual arrival and departure times for all shippers that cannot be obtained without considerable data gathering. While possibly feasible to measure for one shipper, it would be very difficult to aggregate over many shippers with varied commodity and shipment characteristics.

The Transportation Research Board

(<http://bca.transportationeconomics.org/benefits/travel-time-reliability>) identifies that, in general most researchers believe that the standard deviation or variance of travel time is the most relevant measure for B-C analysis. This difference in opinion may be due to the fact that the TRB is very much concerned with the practical application of B-C analysis and that the measurement of average and standard deviations of traffic flows are relatively easy to measure. However, most surveys designed for valuing travel time reliability do not describe travel time reliability as standard deviation or variance of travel time since these two concepts are recognized as too difficult for most respondents.

If sufficient travel time data is available, e.g. every 5 minute loop detector data, we recommend using the buffer time which represents the extra travel time travelers must add to ensure on-time arrival to measure the travel time reliability. When data is sparse, e.g. low reading frequency GPS data, we suggest using the bimodal approach employed by WSDOT to evaluate the travel time reliability as this method does not require extensive travel time data, but still can examine and classify the reliability based on spot speed data.

Conclusion

This review of existing work and application of multiple methodologies to case study situations demonstrates that there are not only several measures of reliability that may be generally acceptable, but that under the right conditions (appropriate data for each) they produce quite similar results.

Accordingly, the next step in determining the appropriate value to use for time reliability to use in a cost-benefit analysis would be to conduct a survey in the region of interest. A vast literature exists on how to properly execute a stated preference or revealed preference study, and it is beyond the scope of this report to add to that knowledge.

However, Halse and Ramjerdi (2012) and De Jong et al (2004a) provide useful summaries of successful experiments that may serve as templates for future studies.

Until such research is conducted, this report recommends incorporating results using a range of values that are consistent with the results found in previous studies.

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