REPORT S2-L35A-RW-1

Value of Travel Time Reliability in Transportation Decision Making: Proof of Concept—Portland, Oregon, Metro

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The Second

STRATEGIC HIGHWAY RESEARCH PROGRAM

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Value of Travel Time Reliability in Transportation Decision Making: Proof of Concept—Portland, Oregon, Metro

UNIVERSITY OF ARIZONA

in collaboration with

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The Second Strategic Highway Research Program

America's highway system is critical to meeting the mobility and economic needs of local communities, regions, and the nation. Developments in research and technology—such as advanced materials, communications technology, new data collection technologies, and human factors science—offer a new opportunity to improve the safety and reliability of this important national resource. Breakthrough resolution of significant transportation problems, however, requires concentrated resources over a short time frame. Reflecting this need, the second Strategic Highway Research Program (SHRP 2) has an intense, large-scale focus, integrates multiple fields of research and technology, and is fundamentally different from the broad, mission-oriented, discipline-based research programs that have been the mainstay of the highway research industry for half a century.

The need for SHRP 2 was identified in *TRB Special Report 260: Strategic Highway Research: Saving Lives, Reducing Congestion, Improving Quality of Life,* published in 2001 and based on a study sponsored by Congress through the Transportation Equity Act for the 21st Century (TEA-21). SHRP 2, modeled after the first Strategic Highway Research Program, is a focused, time-constrained, management-driven program designed to complement existing highway research programs. SHRP 2 focuses on applied research in four areas: Safety, to prevent or reduce the severity of highway crashes by understanding driver behavior; Renewal, to address the aging infrastructure through rapid design and construction methods that cause minimal disruptions and produce lasting facilities; Reliability, to reduce congestion through incident reduction, management, response, and mitigation; and Capacity, to integrate mobility, economic, environmental, and community needs in the planning and designing of new transportation capacity.

SHRP 2 was authorized in August 2005 as part of the Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (SAFETEA-LU). The program is managed by the Transportation Research Board (TRB) on behalf of the National Research Council (NRC). SHRP 2 is conducted under a memorandum of understanding among the American Association of State Highway and Transportation Officials (AASHTO), the Federal Highway Administration (FHWA), and the National Academy of Sciences, parent organization of TRB and NRC. The program provides for competitive, merit-based selection of research contractors; independent research project oversight; and dissemination of research results.

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FOREWORD

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Transportation agencies have traditionally used average travel times and travel time savings to measure system performance and benefits of improvement investments. The reliability of travel times from day to day has recently emerged as an important component of system performance for agencies and, of equal importance, for users who may rely on the roadway system for on-time arrival at their destinations. Unreliable travel can have significant negative consequences for individuals and businesses and thus requires that the value of reliability be considered in the selection of performance improvement projects. There is a need to understand the benefits of providing reliable travel time, establishing appropriate monetary values, and incorporating the additional dimension of travel time reliability into the economic analysis methods that support alternative project investment evaluations and programming decisions that will lead to better operational performance. This report will be of interest to transportation agencies and professionals involved in the analysis and selection of highway improvement projects for operational and capital programming.

Traffic congestion continues to grow on the nation's highways, increasing the concerns of transportation agencies, the business community, and the general public. Congestion includes recurring and nonrecurring components. *Recurring congestion* reflects routine day-to-day delays during specific time periods where traffic demand exceeds available roadway capacity. Road users come to expect these daily traffic patterns and adjust their travel plans accordingly to achieve timely arrivals. *Nonrecurring congestion* results from random incidents such as crashes, weather, and work zones, which cause unexpected extra delays. Road users are frustrated by these unexpected delays, which can make for late arrival times at their destination. The SHRP 2 Reliability research objective focuses on reducing nonrecurring congestion through incident reduction, management, response, and mitigation. Achieving this objective will improve travel time reliability for both people and freight.

This report documents and presents a pilot approach at the regional planning level to develop, justify, apply, and assess the impact of travel time reliability as a dimension in the economic analyses that support project investment evaluations. The pilot approach had a multimodal focus that addressed both automobile and public transit trip reliability impacts. Background research was conducted to select the travel time reliability metrics for use in the pilot, as well as to establish an understanding of the value of reliability. The research results served as the basis to engage the regional stakeholder agencies in a collaborative exercise to establish a locally agreeable value of reliability as an input to analytical modeling application. The modeling framework involved replacing the common static traffic and transit assignment with a dynamic transportation network assignment for both traffic and transit. This network assignment could measure travel times and reliability for both modes to serve the development of generalized cost estimates and establish monetary values for the value of travel time and reliability. The model framework was applied to a single corridor, under baseline and future traffic conditions. The cost-benefit impacts of various competing improvement scenarios were assessed considering both travel time and travel time reliability. Business processes that compare operational alternatives with more traditional capital improvements were evaluated and ranked. The approaches, methods, and findings of this pilot application could be informative to other agencies and jurisdictions that have an interest in adopting and incorporating travel time reliability into their project development and programming decision-making process.

CONTENTS

Executive Summary

The objective of the second Strategic Highway Research Program (SHRP 2) Reliability Project L35A, The Estimation and Use of Value of Travel Time Reliability for Multi-Modal Corridor Analysis, is to demonstrate viable local methods for estimating reliability measures, as well as the economic value of travel time reliability that is agreeable to the local modeling and policy group within a context of transportation decision making.

The principal research activities include (1) increasing policy makers' situational awareness through a workshop engagement (the first one), (2) obtaining a value of travel time reliability that is locally acceptable for the demonstrative nature of this project, (3) applying such a value to an integrated regional travel demand model and dynamic traffic and transit assignment modeling approach, (4) setting up and evaluating a wide range of scenarios, and (5) presenting the research findings to the same policy groups, obtaining feedback and comments regarding the overall modeling exercise and assessments of potential future use of reliability in actual project analysis.

The Portland Metro policy group to adopt a simplified stated-preference method via an online survey to estimate the reliability ratio (RR) that can be used to estimate the value of travel time reliability. Although this is a highly simplified method, the estimated RR value appears to be comparable with the literature and was confirmed to be acceptable for further project scenario modeling activities.

To better account for the time-varying nature of traffic dynamics and to further leverage the prior SHRP 2 research products, the research team applied the state-of-the-art network models to better capture the needed sensitivity with respect to reliability. The research team integrated Metro's trip-based travel demand model with the dynamic traffic assignment model DynusT (for **Dyn**amic **U**rban **S**ystems for **T**ransportation) and the dynamic transit assignment model FAST-TrIPs (for **F**lexible **A**ssignment and **S**imulation **T**ool for **Tr**ansit and **I**ntermodal **P**assenger**s**) in this project. Both of the latter models were based on the research products associated with the SHRP 2 C10B project. SHRP 2 L35A is the first project that is able to demonstrate successfully the feasibility of integrating the network models from SHRP 2 C10B with a trip-based model.

More than 10 scenarios were identified and modeled in this project. The analysis results indicate that both bus rapid transit and variable message signs contribute to improved reliability for the Southwest Corridor when the performance over multiple modes and facilities is being considered. Bus rapid transit contributes to improved corridor performance by increased ridership due to higher reliability, and variable message signs contribute to improved corridor reliability by balancing the arterial and freeway flow via information dissemination.

Such modeling processes and results were fully presented and discussed at the second workshop with the Metro policy group. The policy group members concluded that incorporating reliability into the overall scenario and project analysis helped them to better understand the potential benefit of studied strategies that could not be otherwise realized within the traditional method.

CHAPTER 1

Introduction

Travel time reliability is a significant aspect of transportation system performance. Recent work has shown that reliability has value to travelers and that their behavior is influenced by it. A wealth of research findings related to the second Strategic Highway Research Program's (SHRP 2) Reliability Program has provided numerous instances of theoretical and empirical evidence for this fact. Reliability influences decisions about where, when, and how to travel. Because of the extra economic cost of unreliable travel on users, it has been increasingly recognized that transportation planners and operators need to include these costs in the project planning, programming, and selection process.

SHRP 2 has launched several studies investigating theoretical and practical methodologies to measure, value, and predict automobile travel time reliability. In the present project, the L35A research team sought to develop a theoretically sound, practical, viable, and flexible local method based on prior related SHRP 2 project findings to incorporate travel time reliability into the project evaluation process for multimodal project planning and development. In other words, this project does not attempt to "reinvent the wheel" and repeat the research activities undertaken by prior SHRP 2 projects but to build the knowledge formulated by these various studies into an integrated framework and procedure in a practical real-world case study that effectively engages policy makers and elevates their understanding and confidence that SHRP 2 Reliability research products can properly represent project performance characteristics and inform decision making.

The two foundational bodies of knowledge for L35A are SHRP 2 L03 and C10B. The L03 project developed an analytical framework and procedure to estimate reliability measures for a traffic network. In a nutshell, Reliability project L03 established various relationships between the mean and variance of travel time. Generally speaking, the higher the mean travel time is, the higher the travel time variance is. The proposed method also accounts for nonrecurrent event–induced travel time variance. The advantage of this framework for regional modeling lies mainly in its computational tractability because this method does not require running Monte Carlo simulation–type random processes such as those proposed in the SHRP 2 L04 Reliability project.

The second building block for this project is the fine-grained, multimodal dynamic traffic simulation and assignment network models created from SHRP 2 C10B. Multimodal models capture travel time reliability for both automobile traffic and public transit services. These integrated network models allow the modeler to depict time-varying network traffic dynamics that, through the skim feedback process, can better inform the travel demand forecasting model in estimating trip generation and distribution.

The agency member of this project, metropolitan planning organization Portland Metro of Portland, Oregon, is a pioneering transportation planning agency that has adopted many innovative modeling techniques in the last few decades. Metro modeling staff once suggested a desire to assess hours of congestion and reliability measures in the project evaluation process, but they never implemented that wish because Metro's existing travel demand model cannot forecast unreliable areas in the existing framework.

Traffic reliability was introduced in the *Transportation Existing Conditions Report* using INRIX data from the past 3 years to illustrate a buffer index using the 95th percentile travel time compared to average travel time. This report marked the first time Metro addressed reliability in its reporting, and addressed in combination with a congestion map (also produced using INRIX), the reliability map was useful in identifying transportation needs. Leveraging the research methodologies and outcomes produced by this research, Metro was able to use reliability measures to improve the development of Metro's overall transportation improvement program and specific project programming. In this way, projects intended to provide either a primary or a secondary benefit in improving travel time reliability can be prioritized like any other project.

1.1 Research Goals and Scope

The overarching goal of L35A is to establish a locally acceptable method for determining the value of travel time reliability (VTTR) and show how to apply such obtained values, as well as travel time reliability measures, to project evaluation and program development following a defined modeling process. Critical objectives serving this goal included the following:

1. Developing travel time reliability measures. The adopted method primarily follows the L03 framework and approach (in lieu of Monte Carlo simulation types of methods, such as those used in SHRP 2 L04) to facilitate the computational requirements of regional modeling;
2. Developing a locally accepted method to estimate the value of reliability. Such a method was originally proposed to be adopted from the literature review, but the actual method used is a simplified stated-preference model similar to that used in a recent Dutch study (Significance et al. 2013);
3. Generating reliability measures in a multimodal, dynamic traffic assignment (DTA) framework to allow reliability measures to be captured in a time-varying manner;
4. Revising Metro's existing project evaluation process to incorporate VTTR in an integrated feedback framework;
5. Presenting results from a real-world case study on how travel time variability affects cost-benefit results and project ranking and discussing what previously unavailable insights could be supported by the analysis afforded by the proposed integrated modeling approach;
6. Providing a case study that would be primarily conducted by the technical staff of the participating transportation agency. This requirement allowed the agency staff to obtain realistic first-hand experience and thus be able to arrive at a realistic assessment of user and market readiness of the SHRP 2 research products; and
7. Presenting the research findings to local stakeholders and learning whether the proposed overall methodology and findings elevated their understanding and willingness to continue adopting reliability measures in future project assessment and selection processes.

1.2 Overview of the Research Framework

The overall research framework is illustrated in Figure 1.1. The top left of the figure shows a modified representation of the traditional steps in travel demand modeling, but replacing the common static traffic and transit assignment with a dynamic transportation network assignment that covers both road travel and dynamic transit assignment. The dynamic traffic and transit assignment models used in this project are fully capable of capturing time-dependent, travel time variability through a variety of measures of performance. As a result, a critical advantage of the framework is that reliability can be captured for both automobile and transit travel, capturing multimodal measures of travel times and of travel time variability.

The result of the dynamic transportation network assignment process is a set of metrics on automobile users' and transit passengers' travel times and travel time variability. Using these existing and emerging methods, which have been well documented in other SHRP 2 Reliability projects, the travel times and variability measure(s) can be used to determine a resulting generalized cost of travel. In this project we chose the methodology proposed by SHRP 2 Project L03 Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies (Cambridge Systematics 2013a). This method allows the recurrent- and nonrecurrent congestion–induced reliability measures to be computed analytically, accommodating the computational requirements for large-scale modeling.

These reliability measures can be fed back to the travel demand modeling process for the purposes of capturing the effects of reliability in both mode split and trip distribution steps. This procedure continues in an iterative manner until the generalized cost is convergent and stable.

The convergent travel times and travel time variability measures from dynamic network assignment can then be converted into more direct measures of generalized cost and/or generalized time. This conversion is important because it allows direct monetization of VTTR and the value of travel time (VOTT). These two measures, which have been extensively studied through the SHRP 2 program and in previous research, give greater economic meaning to the value of reliability. We then have the ability to convert the generalized cost (or time) into a total measure of benefit (or cost) to travelers under certain projects and under given planning scenarios.

These benefits and/or costs, comprising both travel time and reliability, can be turned into criteria fitting into the existing project evaluation process. Portland Metro's existing project evaluation criteria include, but are not limited to, traffic volume, capacity ratio, vehicle miles, automobile and transit travel times, average automobile and transit work trip travel times, and in-vehicle transit travel times.

1.3 Modeling Platform and Framework

1.3.1 Metro Existing Travel Demand Model

The current Metro demand model is considered to be an enhanced trip-based demand model. It has gained the accreditation of the Federal Transit Administration and the Federal Highway Administration for use in infrastructure investment projects.

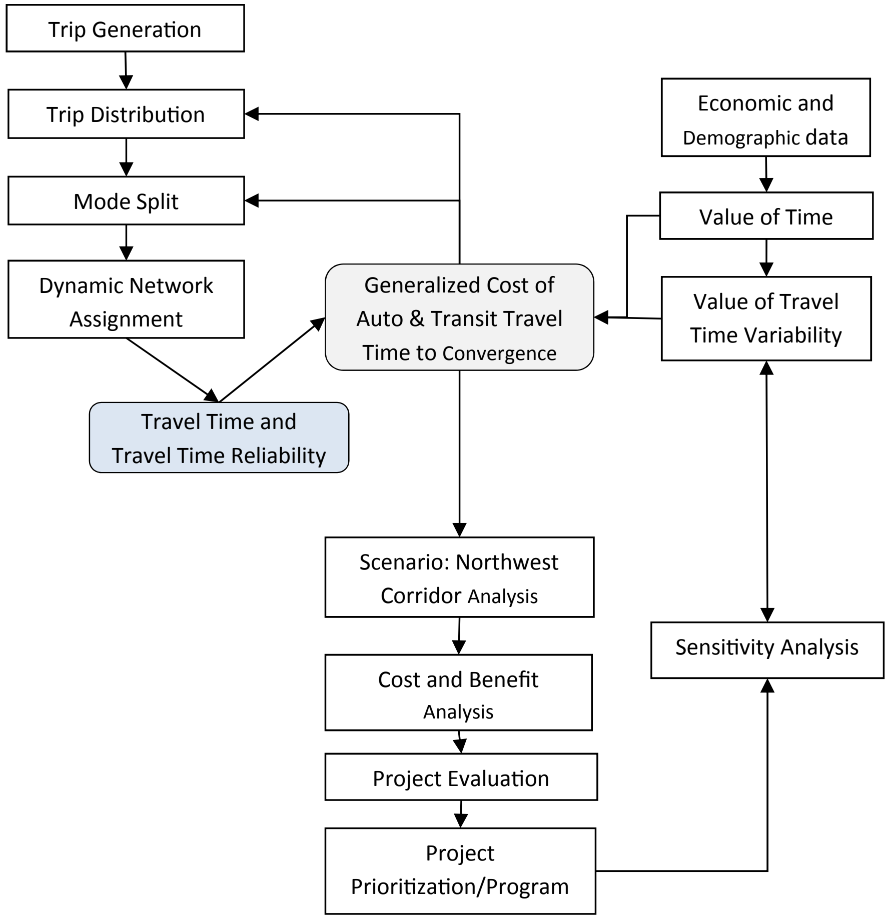


Figure 1.1. Overall model framework.

1.3.1.1 Inputs

Demographic data for input into the demand model process included the number of households in each traffic analysis zone stratified by household size, income group, and age of household head. Employment data were stratified by nine employment categories. Several separate models were created to provide inputs into different steps of the model. These included models to estimate the number of workers, number of children, and automobile ownership by household categories.

Urban form descriptors, which refer to the spatial pattern of urban activities, are an important part of the model due to their influence on trip making. An accessibility measure was calculated that reflected the proximity of households to shopping and job opportunities. Local intersection density was also determined.

Transportation system supply data were created for the purpose of determining travel times and generalized costs. Travel time data were created for two time periods, an AM peak two-hour period and a midday one-hour period, for the auto, transit, park-and-ride, walk, and bike modes. Transit skims included in-vehicle, walk, first wait, transfer wait, and number of transfers. Trip cost data included automobile operating costs, parking costs, and transit fares. Household survey data were used to estimate the percentage of peak versus off-peak travel for each trip purpose and were used in mode choice.

1.3.1.2 Trip Generation

The trip generation step created trips for eight trip purposes: home-base work, home-base shopping, home-base recreation, home-base other, non-home-base work, non-home-base non-work, home-base school, and home-base college. For each traffic analysis zone, the number of households in specific demographic categories was multiplied by a production rate. For example, for the home-base work trips, the trips were calculated using the number of workers in the household, which was calculated in the worker model.

For home-base work and home-base college, trip attractions were calculated and productions and attractions were balanced during destination choice. For the other trip purposes, attractions were not calculated directly; the productions were singly constrained. The magnitude of employment (by type and associated parameter) served to indicate the relative attractiveness of a destination zone during destination choice.

1.3.1.3 Destination Choice

The destination choice models were developed using a multinomial logit estimation procedure. Each of the eight trip purposes had a separate set of variables and coefficients. Household trips by income levels were distributed separately with different variables and coefficients for each stratum, including the employment categories at the destination zone. This feature allowed households to be linked with jobs that reflected an appropriate level of income. Logsums were used in the destination choice step to provide sensitivity to changes in multimodal accessibility. These logsums were created from the variables and coefficients used in mode choice.

1.3.1.4 Mode Choice

The mode choice models were developed using a multinomial logit estimation process. Household characteristics such as income level, automobile ownership, and household size were used, as well as travel time, urban form descriptor, and cost variables. The modes included in the demand model were drive alone, drive with passenger, auto passenger, walk access transit, auto access transit, bike, and walk.

An important model feature was the incorporation of results from a stated-preference study that quantified travelers' perceptions of different transit vehicles and transit stops. The model reflects the differences in how travelers view in-vehicle time by vehicle type (i.e., bus, rail) as well as the type of stop (i.e., large transit center, small shelter, and pole stop). Another notable feature was the creation of a formal bike utility that reflects the attractiveness of a bike route as measured by key indicators (e.g., gradient, bike lanes/paths/trails, ambient traffic, intersection controls). The park-and-ride mode now has an element concerning lot choice based on a lot's utility; this element also responds to lot capacity constraints.

An important element in the model is the delineation of time periods. Trips for each type of purpose were stratified into those made during peak periods and off-peak periods. Each time stratum was populated with attribute values that reflected the characteristics of the temporal period.

1.3.1.5 Trip Assignment

For the static automobile assignment, a capacity-restrained equilibrium assignment was used. Transit assignments were also performed. For most scenarios, a PM two-hour peak and a midday off-peak assignment were analyzed. Feedback mechanisms were in place because the travel times are fed into the demand model during the iterative process. Metro has also developed DTA capabilities for use in project analysis.

1.3.2 Multimodal Simulation and Assignment Framework (DynusT and FAST-TrIPs)

The University of Arizona has developed an integrated framework for dynamic automobile and transit assignment and simulation by using the open source software tools DynusT (**Dyn**amic **U**rban **S**ystems for **T**ransportation) and FAST-TrIPs (**F**lexible **A**ssignment and **S**imulation **T**ool for **Tr**ansit and **I**ntermodal **P**assenger**s**). The interactions of these two software tools are described in Section 5.3. DynusT has been used extensively as a DTA tool in the United States, including playing leading roles in SHRP 2 Projects C10B and L11, and in many local applications and deployments of DTA. The FAST-TrIPs software tool has also been used in several recent projects, including SHRP 2 Project C10B.

DynusT is used by Portland Metro, which has developed a working regionwide DTA-compatible automobile network. Network attributes include lanes, speeds, and facility types, as well as intersection-level details (number of turn bays, length of turn bays, lane-to-lane movements, signal phasing, and permitted–protected left-turn treatments). This network can be easily imported into any of several DTA packages, including DynusT.

In addition, Metro has worked on improving input trip tables for use in DTA. Currently, Metro is able to produce trip tables segmented into 15-min demand periods. These trip tables come directly from the travel demand model and are easily formatted to work with any DTA package, including DynusT. Figure 1.2 illustrates the Portland Metro DTA model in DynusT.

The team also adapted the existing transit data at Metro to develop and implement FAST-TrIPs for Metro. This involved converting Portland Trimet files corresponding to Google's General Transit Feed Specification (GTFS) into a network format that matched the DynusT network.

Three main parts of the integrated model are differentiated. The demand model, in the form of a tour-based (or activity choice) travel demand model, provides the outputs, containing travelers with a given origin, destination, preferred arrival time, and transportation mode. These data are separated into auto, transit, and intermodal trips and are fed into the assignment models in DynusT and FAST-TrIPs. As a DTA model, DynusT includes transit vehicle simulation, as well as auto and truck vehicle simulation. For the initial transit run in DynusT, a fixed dwell time of the transit vehicles is assumed and fed into the first iteration of the simulation. The main outputs of the DTA model are auto skims, which are used to check the convergence of DTA and are also fed back to the travel demand model to adjust the demand for the next iteration. Another

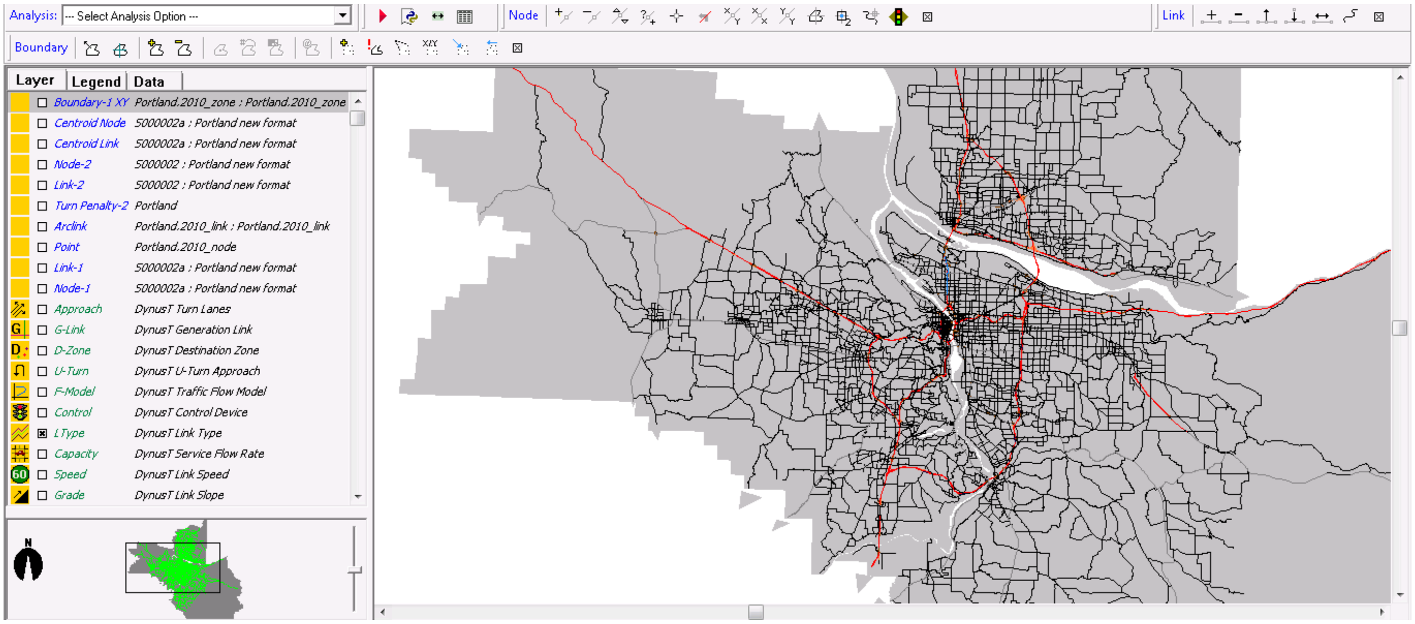


Figure 1.2. Portland Metro DynusT model.

output of DynusT is the vehicle trajectories, including the departure times of the transit vehicles at each stop, which are passed to FAST-TrIPs to simulate passenger movements in the transit network.

The transit part of the model receives the vehicle skim by the experienced vehicles, including public transit vehicles, and simulates the passengers in the transit network using the path choices coming from the transit assignment. Passengers are assigned on a transit schedule network according to their stochastic behavior along a given hyperpath in which every passenger will have an elementary (or single) path. Passengers are then simulated along the assigned paths, on which it is possible to have some missing-a-bus cases caused by late arrival or capacity constraint. As iterating the integration model continues, the passengers with missing-a-bus will disappear as link travel times are converged. Ultimately, the transit simulation in FAST-TrIPs produces a transit skim with access, waiting, in-vehicle, and transfer times. The boarding and alighting results from the simulation are used to generate vehicle dwell times, which are used in the next iteration of the vehicle simulation in DynusT. Finally, the transit skim data are fed back into the travel demand model.

1.4 Report Structure

This report is structured as follows:

- Chapter 2 provides an overview of the integrated model.
- Chapter 3 presents the agreed local method for determining reliability measures and VTTR.
- Chapter 4 discusses the process for prioritizing operational and capital improvement.
- Chapters 5 through 7 describe the modeling and scenario analysis details.
- Chapter 8 describes the second workshop, in which the research findings were presented to the policy group and feedback was collected.
- Chapter 9 concludes this report.
- Chapter 10 lists all cited literature.
- Appendix A presents the Southwest Corridor work plan.
- Appendix B describes the DynusT–FAST-TrIPs integration run shown in DynuStudio.

CHAPTER 2

Overview of DynusT–FAST-TrIPs Integrated Model

2.1 DynusT

2.1.1 DynusT Model Structure

As shown in Figure 2.1, DynusT consists of iterative interactions between its two main modules, traffic simulation and traffic assignment. Vehicles are created and loaded into the network based on their respective origins and follow a specific route based on their intended destinations. The large-scale simulation of networkwide traffic is accomplished through the mesoscopic simulation approach, which omits intervehicle car-following details while maintaining realistic macroscopic traffic properties (i.e., speed, density, and flow). More specifically, the traffic simulation is based on the anisotropic mesoscopic simulation (AMS) model, which simulates the movement of individual vehicles according to the concept that a vehicle's speed adjustment is influenced by the traffic conditions in front of the vehicle. In other words, at each simulation interval, a vehicle's speed is determined by the speed–density curve, and density is defined as the number of vehicles per mile per lane with a limited distance—defined as the speed-influencing region (SIR)—downstream of the vehicle (Chiu et al. 2010).

After simulation, necessary measures of effectiveness (MoEs) are fed into the traffic assignment module. The traffic assignment module consists of two algorithmic components: a time-dependent shortest-path (TDSP) algorithm and time-dependent traffic assignment. The TDSP algorithm determines the TDSP for each departure time, and the traffic assignment component assigns a portion of the vehicles departing at the same time between the same origin–destination (O-D) pair to the time-dependent least-travel time path following a "route swapping" type of traffic assignment procedure.

In DynusT, the assignment algorithm adopts the isochronal vehicle assignment method (Nava and Chiu 2012), which aims to maintain a balance between computational efficiency and solution algorithm quality. Innovations in computational efficiency allow DynusT to perform 24-hour assignment, a feature that was critical for estimating daily traffic patterns for the purpose of this study. The computational features include (1) reusing vehicle IDs to commit computer memory only for those vehicles that exist in the network during simulation so that memory usage is not cumulative to the total number of generated vehicles, and (2) assigning vehicles with TDSPs that are solved based on an epoch, which is the time period over which network statistics are collected for solving for the TDSP. An epoch was defined as about one to two hours in length. The memory usage for the TDSP is limited by the length of the epoch regardless of the length of the total evacuation simulation period.

Once the assignment of the current iteration is finished, all vehicles are again loaded and moved along their paths in the simulation module to evaluate if the time-dependent user equilibrium (TDUE) condition is satisfied. If so, the algorithmic procedure is terminated; otherwise, the next iteration begins.

2.1.2 Anisotropic Mesoscopic Traffic Simulation

The AMS model was developed based on two intuitive concepts and traffic characteristics: (1) at any time, a vehicle's prevailing speed is influenced only by the vehicles in front of it, including vehicles that are in the same or adjacent lanes; and (2) the influence on a vehicle of traffic downstream decreases with increased distance. These two characteristics define the "anisotropic" property of the traffic flow and provide the guiding principle for AMS model design. Based on such concepts, for any vehicle i, only those leading vehicles present in vehicle i's immediate downstream area and within a certain distance are considered to influence vehicle i's speed response. This concept is a similar concept to a stimulus–response type of car-following model, with the distinction that in AMS, the stimulus of a vehicle's speed response is represented in a macroscopic manner instead of using intervehicle distance or speed as in microscopic models.

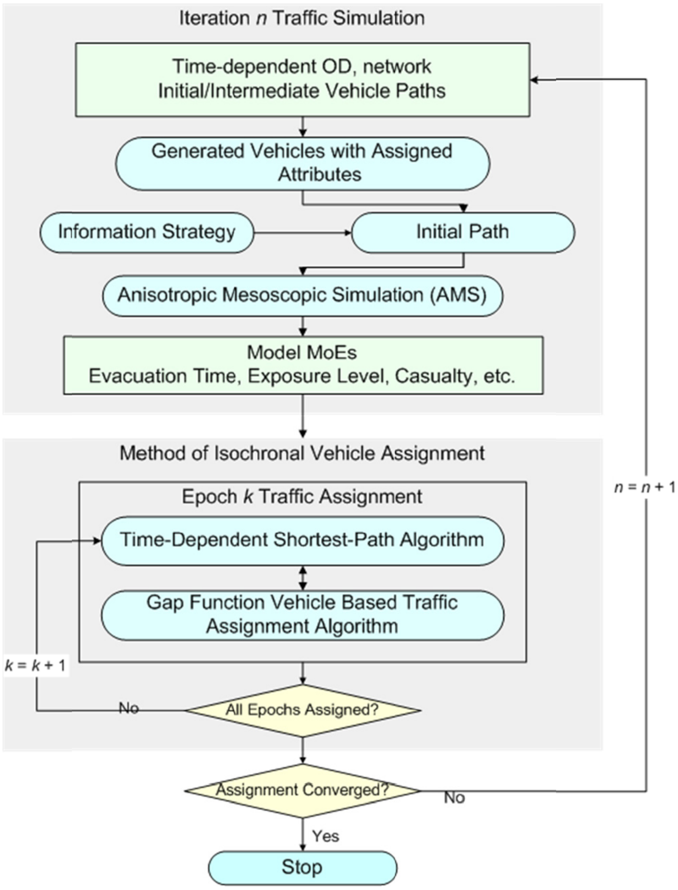


Figure 2.1. DynusT model algorithmic structure.

For modeling purposes, the speed-influencing region for vehicle i (SIR_i) is defined as vehicle i's immediate downstream roadway section in which the stimulus is significant enough to influence vehicle i's speed response. This concept is further depicted in Figure 2.2, in which a multilane, homogeneous roadway segment is considered. The SIR for vehicle i is defined as the area (including the lane in which vehicles reside and all the adjacent lanes) in front of vehicle i, where the traffic condition (represented by the density) affects vehicle i's speed response. At each simulation clock tick, vehicle i's speed is influenced by the density in SIR. The upstream and downstream traffic outside the SIR does not influence vehicle i. The SIR_i length can be assumed to be either equal for all vehicles or variable according to different flow conditions. In this study SIR_i length was assumed to be an average value l across all vehicles. The traffic density in SIR_i, denoted as k_i, is calculated as the number of vehicles present in SIR_i divided by the total lane miles of SIR_i. As such, the unit of k_i becomes the number of vehicles per mile per lane.

At the beginning of a simulation interval t, for each vehicle i, the prevailing speed of vehicle i during the simulation interval t is determined by Equation 2.1, where $\wp: k \to v$ is a nonincreasing speed–density relationship function with two boundary conditions: $\wp(0) = v_f$ and $\wp(k_{\text{queue}}) = 0$. The queue density k_{queue} is defined as the "bumper-to-bumper" density observed in a long, standing-still queue, which is generally greater than the jam density reported in the literature.

The algorithmic steps of an AMS model during simulation are as follows. At each clock tick t (the beginning of a simulation interval), each vehicle's speed v_i^t is evaluated based on its SIR density, which is obtained from the previous clock tick k_i^{t-1} through the v-k relationship function $\wp(k_i^{t-1})$. The SIR density is calculated based on Equation 2.2 or 2.3, depending on whether the SIR spans over the freeway segment with a different capacity. If the SIR spans a homogeneous highway section, Equation 2.2 applies; otherwise, Equation 2.3 is used. Vehicle i's traveling distance at the end of the current simulation interval is obtained by taking the prevailing speed v_i^t times the duration of the simulation interval Δ.

$$v_i^t = \wp\left(k_i^{t-1}\right) \tag{2.1}$$

$$k_i^{t-1} = \min\left[k_{\text{queue}}, \frac{N_i^{t-1}}{nl}\right] \tag{2.2}$$

$$k_i^{t-1} = \min\left[k_{\text{queue}}, \frac{N_i^{t-1}}{mx_i^{t-1} + n\left(l - x_i^{t-1}\right)}\right] \tag{2.3}$$

where

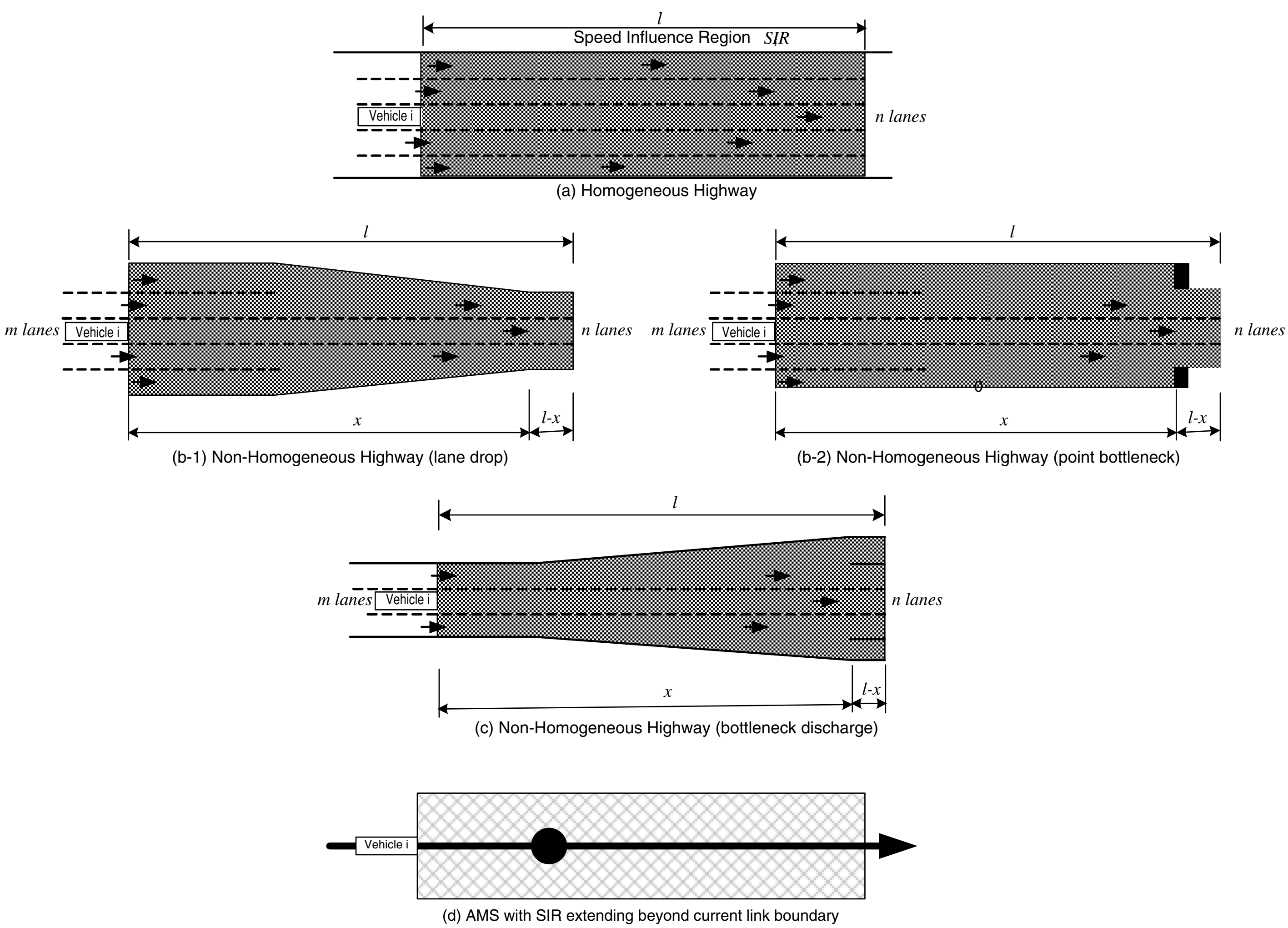
- i: subscript denoting a vehicle. The index i decreases with vehicles traveling in the same direction on the same link;
- t: superscript denoting a simulation interval;
- l: SIR length;
- v_i^t: prevailing speed of vehicle i during simulation interval t;
- x_i^{t-1}: distance between vehicle i and lane drop (open) at clock tick $t-1$;
- k_i^{t-1}: density of SIR for vehicle i;
- N_i^{t-1}: number of vehicles present in SIR, excluding vehicle i;
- v_f: free-flow speed in the speed–density relationship;
- $\wp: k \to v$: nonincreasing speed–density function specifying the v-k relationship, where $\wp(0) = v_f$ and $\wp(k_{\text{queue}}) = 0$; and
- k_{queue}: queue density, $\wp(k_{\text{queue}}) = 0$.

During the AMS simulation, each vehicle maintains its own prevailing speed and SIR at the beginning of a simulation interval. The traveling distances of individual vehicles are therefore likely to differ, even though they are on the same link. This feature is different from certain previous models (Jayakrishnan et al. 1994; Balakrishna et al. 2005) in which all moving vehicles on the same link travel at the same speed. This difference characterizes the AMS model as a vehicle-based mesoscopic model having a greater degree of resemblance with car-following–based microscopic models. The major difference between AMS and car-following models is that in AMS, a vehicle's speed adjustment at each simulation time interval is governed by the SIR density k_i^t, which is a macroscopic measure of all the vehicles present in the SIR region, instead of an intervehicle measure between the target and the leading vehicle(s).

Because the SIR moves with each vehicle during simulation, it can be anticipated that in the AMS model, the vehicle-advancing mechanism is generally independent of the representation of network structures (i.e., the size or length of the cell, segment, or link) under the uninterrupted flow condition. Each vehicle makes speed adjustment decisions solely based on its SIR density; the AMS simulation results generally remain stable regardless of how link lengths are defined unless the link is shorter than a certain threshold that violates the one required by a general time-based simulation.

AMS handles queue formation and discharge in a natural and straightforward manner. When k_{queue} is reached, $v = \wp(k_{queue}) = 0$; vehicles speed up when the SIR density decreases. This mechanism allows for clear representations of substantial or transient queue formation or discharge. When a free-moving vehicle approaches the end of a queue, its speed gradually approaches the same speed of the queue tail as its SIR density approaches the SIR density of the leading vehicles. Depending on how the overtaking condition is met, this vehicle may trail at the end of the queue without "jumping over" leading vehicles, or it may stop ahead of the leading vehicle.

Equation 2.1 was further extended to simulate traffic flow in uninterrupted flow facilities under various configurations, such as homogeneous highways, nonhomogeneous highways, and temporary blockage, by specifically considering different SIR density k_i^t calculations corresponding to those conditions. As shown in Equation 2.2, in the case of the homogeneous highway, k_i^t is calculated as the number of vehicles present in the SIR divided by the total number of lane miles of the SIR (i.e., the SIR length times the number of lanes). When lane drops or lane additions occur within the SIR, the total lane miles of SIR are the sum of the lane miles of separate sections, as shown in Equation 2.3. The lane drop (Figure 2.2b-1) or



Source: Chiu et al. 2010.

Figure 2.2. AMS model concept.

point bottleneck (Figure 2.2b-2) (from m to n lanes, $n < m$) occurs downstream from vehicle i. The total lane miles in the SIR are calculated as $mx + n(l - x)$, and the resulting k_i^t is the smaller of k_{queue} and $\frac{N_i^{t-1}}{mx + n(l - x)}$, which is the number of vehicles in the SIR at the beginning of time interval $t - 1$ divided by the total lane miles $mx + n(l - x)$ in the SIR.

In the case of a lane drop or a point bottleneck ($n < m$), the SIR density of a vehicle gradually increases (and hence speed reduces) as it approaches the bottleneck. When $n = 0$, a complete blockage occurs that can be applied to either the point blockage or red-light signal indication. In the case of discharging from a bottleneck, as a vehicle approaches the opening up of the bottleneck, the density reduces and speed increases gradually.

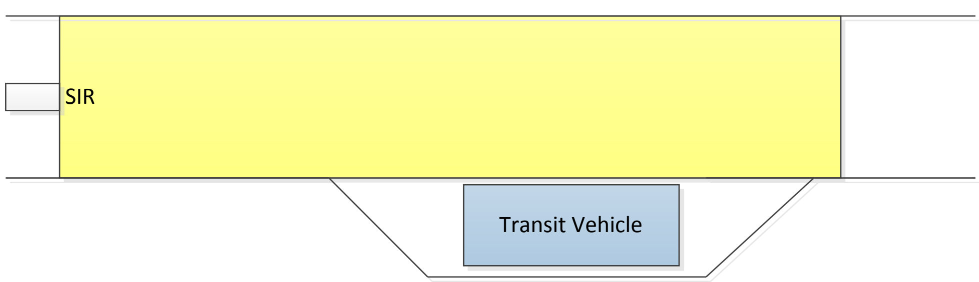
Vehicle simulation under the presence of transit vehicles needs to properly differentiate the situation with or without bus pullouts. As illustrated in Figure 2.3a, when a bus pullout is present and a transit vehicle resides in the pullout, the SIR area of passing vehicles remains unchanged. Without the pullout (Figure 2.3b), the stopped transit vehicle typically blocks one traffic lane, creating a temporal blockage to the traffic downstream. The SIR area of the approaching vehicles is modified as shown in Figure 2.3b, which leads to a slowdown effect similar to the one due to lane drop in Figure 2.2b-1. The departure from each stop involves different rules for frequency- or schedule-based transit. For a schedule-based transit operation, a transit vehicle must be held until the scheduled departure time if it is ahead of schedule after boarding and alighting. Such vehicle holding is unnecessary in a frequency-based operation.

2.2 FAST-TrIPs

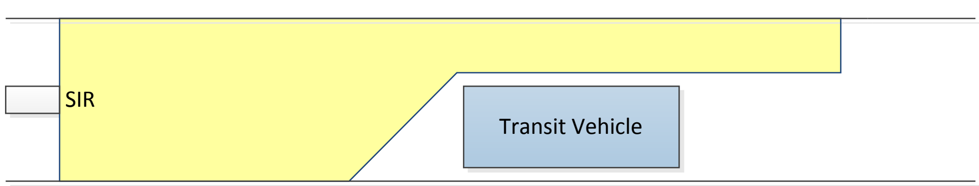
For the transit component, FAST-TrIPs is divided into two main submodules, transit assignment and simulation. The transit assignment submodule plays the role of passenger assignment for given O-D pairs considering the capacity constraint of each transit vehicle. For assigning transit passengers for the O-D pairs, a hyperpath model (Noh et al. 2012) is activated by searching a feasible strategic path on each O-D pair. Since each hyperpath has multiple alternative links for each predecessor link, at least one single path, a so-called elementary path, is generated on a hyperpath. Each passenger is loaded on the specific elementary path according to the probability chosen by a logit model. The assigned passengers, including their path, are given to and simulated through the submodule transit simulation in FAST-TrIPs. During the simulation, experienced arrival and departure times of transit vehicles are used to simulate boarding and alighting of passengers, considering transfers and other components (i.e., walking and waiting). Each passenger's trajectory (i.e., experienced path) is recorded, and dwell time for each transit route is calculated as a function of the boardings and alightings at each stop. The results of the simulation are used in the next iteration of auto–transit vehicle simulation, and they are also fed back to the activity-based model for updating the demand when the DynusT–FAST-TrIPs integration model converges.

2.2.1 Passenger Assignment

For considering passenger strategic choice on a set of routes at each stop, a hyperpath model is introduced on a link-based time-expanded (LBTE) transit schedule network (Noh et al. 2012). To apply the hyperpath model, an LBTE transit



(a)



(b)

Figure 2.3. (a) SIR area with bus pullout and (b) SIR area without bus pullout.

schedule network is prepared. The basic unit of the LBTE transit network is defined on each link, which connects two consecutive stop time runs by an identical transit vehicle. Crucial time information, such as departure and arrival times, is allocated on each schedule link. Like a turn penalty between two successive links, waiting and transfer times are included in the attributes of the LBTE transit schedule network. All time-related information is represented in a generalized cost in the hyperpath search.

On the prepared LBTE transit network, a hyperpath search model is applied to generate the optimal hyperpath. The fundamental hyperpath model was proposed by Nguyen and Pallottino (1988) and Spiess and Florian (1989) in terms of understanding a passenger's strategy on a frequency-based transit network. Divergent hyperpath models have been applied on transit schedule-based networks (Hamdouch and Lawphongpanich 2008). In the LBTE transit network, a hyperpath is generated in a recursive manner by updating the generalized cost from the origin to all destinations by a forward search, or from the destination to all origins by a backward search. For example, consider a network with three links a_1, a_2, and a_3, as shown in Figure 2.4, and assume a backward search from the destination. $\hat{c}_{a_2}$ and $\hat{c}_{a_3}$ are the labels of links a_2 and a_3, respectively. Assuming that those two labels are given or have been updated, the label of link a_1 is updated by a weighting function of link a_2 and a_3 or hyperlink e_3 and the cost of link a_1, c_{a_1}, so that $\hat{c}_{a_1} = c_{a_1} + w(\hat{c}_{a_2}, \hat{c}_{a_3})$, where $w(\cdot)$ stands for a weighting function of the hyperlink e_3 with two alternative links, a_2 and a_3. For the appropriate weighting function on this transit schedule network, Noh et al. (2012) proposed a logsum-type function.

For the hyperpath search, we use the acyclic property of a transit schedule network to determine an efficient search algorithm. The acyclic property of the LBTE transit network holds that every transit link is connected to the next successive link only if the first link arrives at or before the departure time of the next link. According to this acyclic property, a hyperpath is searched in order of the latest departure time, from a destination to all possible origins, by using a backward search. More detail on this algorithm is given in Noh et al. (2012). For better computational performance, a hierarchical hyperpath model was implemented by Khani et al. (2012). In addition, as a backward search is employed, the hyperpath search is assumed to be initiated with a preferred arrival time at the destination.

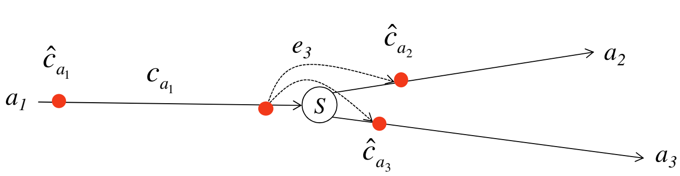


Figure 2.4. Hyperpath on an LBTE transit schedule network and cost update.

With the hyperpath model, we use a method of successive averages–type assignment model under the assumption of a congested transit network. First, by implementing a logit-based hyperpath, the proposed model is categorized as a stochastic user equilibrium transit assignment model. However, it is possible to have a certain level of congestion if the number of passengers exceeds the capacity of a transit vehicle. The order of boarding is strictly dependent on priority, depending on whether the passengers are on board or waiting at a stop; at the stop, priority depends directly on the time of arrival at the stop. To represent this congestion, we introduce a "soft" capacity constraint that increases the travel cost when the vehicle capacity is exceeded. This proposed capacity penalty function is exponential in form and is related to the residual capacity r_b of a transit vehicle and the assigned flows for boarding, f_{ab}, as shown in Equation 2.4:

$$c_{ab}^{\text{cap}} = \frac{f_{ab}}{\max[0, r_b - f_{kb}]} e^{\alpha(f_{ab} - \max[0, r_b - f_{kb}])} \tag{2.4}$$

where f_{kb} is the sum of flows having higher priority than flows f_{ab}. To manage the priority of different boarding flows, a diagonalization technique proposed by Sheffi (1984) was applied. The proposed algorithm is given in Figure 2.5.

The proposed algorithm is separated into inner and outer loops, with the inner loop specified in Step 3 (diagonalization) and the outer loop consisting of Step 2 through Step 4. The proposed algorithm starts with all-or-nothing assignment in Step 1. In Step 2, residual capacity is updated only by the flows satisfying the diagonalized equilibrium in Step 3. Step 3 gives a typical method of successive averages–based passenger loading process on the updated network costs. This process continues until the outer loop is converged at Step 4.

After the transit assignment, passenger flows are created by assigning each passenger a specific elementary path that is sampled from their optimal hyperpath.

2.2.2 Passenger Simulation

The passenger simulation model is a high-resolution model capable of simulating the path taken by individuals in the transit and intermodal networks. The main inputs are the paths generated in the transit assignment submodule. There are three categories of data inputs to the passenger simulation:

1. Transit network, including stops, routes, and schedule;
2. Transit vehicle simulation results, including the actual arrival and departure of transit vehicles at each stop; and
3. Passenger objects, including information about each passenger and his or her path choice.

The simulation model is a combination of an event-based simulation and a time-based simulation. Two main modules

Step 1: (Initialization)

- Search the least-cost path
- Load flows on the searched path
- *n* = 0 *

Step 2: (Capacity Update)

- If subloop (from *Step 3 or Step 1*), then capacities are fixed and $n = n + 1$.
- Else (from *Step 4*), residual capacities are changed by new flows and $n = 0$.

Step 3: (Diagonalization)

- Update the cost of network
- ***Step 3.1***: (Auxiliary Flows)
  - Search the least-cost path
  - Load flows on the searched path
- ***Step 3.2***: (Flows update: MSA)
  - $\text{flows}^{n+1} = 1/(1 + n) \cdot \text{flows}^{n+1} + n/(1 + n) \cdot \text{flows}^{n}$
- ***Step 3.3***: (Convergence Test)
  - If satisfied, then go to Step 4.
  - Else then go to Step 1.

Step 4: (Convergence Test)

- If satisfied, then Stop.
- Else then go to Step 1.

* *n*: iteration number.

Figure 2.5. Transit assignment algorithm, using diagonalized method of successive averages (MSA) with hyperpath.

capture the behavior of passengers and their interaction with transit vehicles. The first module captures the access, egress, and transfer behavior of passengers and is a time-based simulation over fixed time intervals. In the same way, the simulation captures the movement of passengers from their alighting stop to either their destination or the next boarding stop (in case of a transfer). The detailed information of each passenger's trip is recorded. The other module takes care of the boarding and alighting of passengers whenever a transit vehicle arrives at a stop. Therefore, an event-based simulation is used for this part, and a transit event is defined as the simulated arrival of a transit vehicle at a transit stop. By looking at different factors such as the number of passengers and type of transit vehicle, a dwell time is calculated for the transit vehicle at the stop. For each transit vehicle, based on the type of route, a capacity is assumed. All the information regarding the boarding, alighting, and passenger load of the vehicles is written in the output files and can be used in the next system simulation and assignment. The model also has a postprocessor for preparing statistics and measures of performance based on the simulation results.

2.3 DynusT and FAST-TrIPs Integration

2.3.1 Model Integration

The original DynusT–FAST-TrIPs model developed in SHRP 2 C10B was incorporated with a tour-based activity model, DaySim, which produces the demand for a DTA model. Similar models of this interaction of activity-based and DTA models include CEMDAP-VISTA (Lin et al. 2008), TASHA-MATsim (Hao et al. 2010), and OpenAMOS-MALTA (Pendyala et al. 2012). When using the demand from DaySim, three tables provide household, tour, and trip data for model input. Trips, including the origin, destination, estimated departure and arrival times, and mode of transportation for a single trip, are necessary as input to the DynusT–FAST-TrIPs model.

The overall integration model is shown in Figure 2.6. The demand inputs for the DTA model are generated by DaySim, and Google's GTFS data are used to generate the transit schedule. First, auto trips are assigned to DynusT, and transit-related trips are assigned to FAST-TrIPs. Second, DynusT is initiated

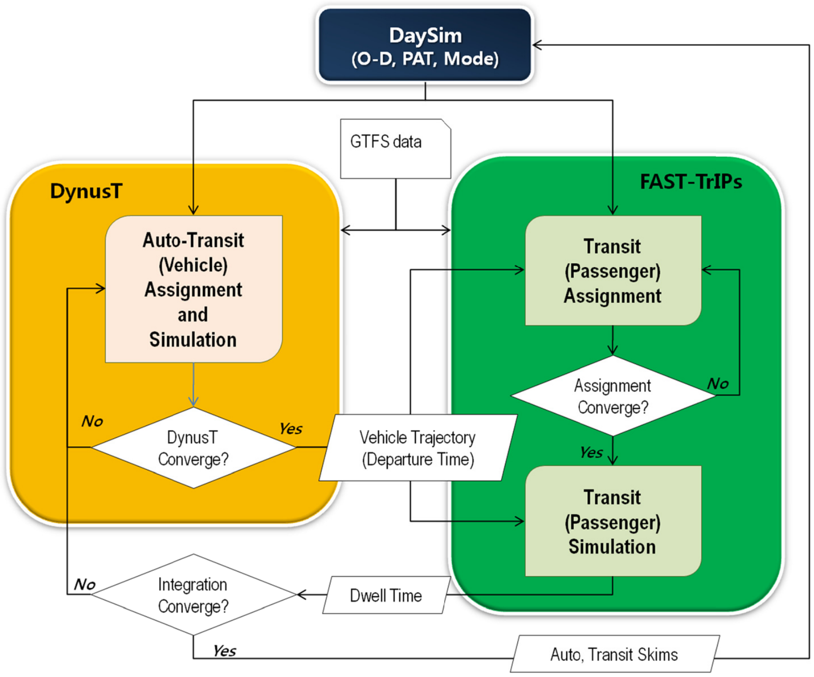


Figure 2.6. DynusT–FAST-TrIPs integration model considering the upper level activity-based model (DaySim is used as an example). PAT = preferred arrival time.

for the assignment and simulation of auto and public transit vehicles. The auto and transit vehicles assignment is run to completion before any input to FAST-TrIPs is generated. Third, the departure times and vehicle trajectories for public transit vehicles are fed into FAST-TrIPs to run the transit passenger assignment and simulation sequentially. As one output of the FAST-TrIPs model, dwell times at each stop are estimated using the number of boarding and alighting passengers at each stop. The estimated dwell times, in turn, will affect the vehicle assignment and simulation in the next DynusT iteration. In this way, the consecutive iterations between DynusT and FAST-TrIPs reach convergence through the consistency of dwell times between the two submodules. Finally, auto and transit (vehicle and passenger) skim tables are produced and returned to DaySim to reach convergence between the demand and supply models.

For Project L35A, DaySim was replaced with the Portland Metro trip-based travel demand model (TDM), and certain modifications were made to enable such integration. First, time-dependent O-D matrices were produced from the Metro TDM system. Different vehicle-type matrices were produced such as high-occupancy vehicle, single-occupancy vehicle, freight, and transit. To enable feedback, five skim matrices were produced to accommodate Metro's five-time-period model. Although the DynusT–FAST-TrIPs integrated system is capable of producing skim information at a much finer resolution, such as 15-min or hourly resolution, aggregation to accommodate a time-of-day model in the trip-based framework was a necessary step.

2.3.2 Convergence

In the DynusT–FAST-TrIPs integration model, three types of convergence apply, as shown in Figure 2.6. Each submodule, DynusT and FAST-TrIPs, has its own individual convergence method for reaching user equilibrium (using a relative gap measure). DynusT uses the simulation-based relative gap measure. The convergence of FAST-TrIPs is estimated by the relative gap of generalized total travel cost, including link travel cost and capacity cost, from one iteration to the next, typically in the transit assignment submodule. Finally, for the combined DynusT–FAST-TrIPs model, we propose a relative gap measure using dwell times to compare dwell time changes from one iteration to the next iteration.

CHAPTER 3

Local Method for Determining Reliability Measures and Value of Travel Time Reliability

3.1 Definition of Travel Time Reliability

According to a recent survey (Cambridge Systematics 2013b), there are two fundamental definitions of travel time reliability:

1. Travel time reliability is defined in terms of travel time variability (i.e., how travel times vary over time, such as hour to hour or day to day).
2. Reliability is defined as the probability that a certain trip (from a given origin to a given destination) can be made successfully within a specified interval of time. This measure is the probability of a "nonfailure over time" and is synonymous with "on-time performance." Within this definition, a clear definition of "failure" in terms of travel time is required.

One significant difference between these two definitions is that the latter measures the variation in individual traveler behavior. The notion of an "on-time arrival" varies from one traveler to another (i.e., depending on whether the individual is risk averse). The magnitude of any desired safety margin for each individual traveler also varies. In comparison, the first definition measures the average variation of all travelers in the system without elaboration of each individual traveler's behavior. One fundamental assumption of the first definition is that travel times among links, and hence among routes, have a continuous probabilistic distribution function. From the standpoint of improving the quality of service, the first definition requires a reduction in travel time uncertainty per se. The second definition, however, also includes adjusting travelers' expectation of travel time variability (i.e., the individual-specific definition of "failure" or "on time"). To specify the research direction more clearly, the definition of reliability in the present project refers to the uncertainty of travel time (i.e., variability) from day to day, but for the same individual trip with the same departure time.

The variance of travel times then contains two parts: variance resulting from recurrent congestion and variance resulting from nonrecurrent congestion. Recurrent congestion is predictable, and experienced individuals may be prepared to accept the variance of travel time for similar trips. Nonrecurrent congestion typically is unexpected, difficult to predict, and more reluctantly accepted by travelers. In this project's definition of travel time variability, the term "reliability" contains the variance of travel time resulting from both recurrent and nonrecurrent congestion. However, if one looks at the travel time variance under recurrent congestion, particular in the day-to-day context, the variability is small and nearly constant; travel time in the peak period is significantly longer than in the off-peak period, but with little uncertainty. Thus, we may represent equilibrium between the variance of travel time from recurrent congestion and travelers' preparedness to deal with the variance of travel time. In comparison, travel time variance caused by nonrecurrent congestion is significant and may cause much larger variability in day-to-day travel times.

3.2 Brief Review of Reliability Studies

3.2.1 Measuring Travel Time Reliability

Table 3.1 summarizes the commonly seen measurements of travel time reliability found in prior research and practice.

3.2.2 Measuring Travel Time Reliability at the Route Level and O-D Level

Mean variance travel time statistics are based on travel time distribution. The travel time distribution is easily assessed on links, but it is difficult to assess on routes and among origin–destination (O-D) pairs. The challenge of measuring route-based variance lies in the correlation of travel times between links. In most practice, it is assumed that link travel times are

Table 3.1. Reliability Measurements

Reliability Measurement	Definition	Annotation
Statistics related		
Mean of travel time (μ)	Mean of travel time	
Standard deviation (σ)	Standard deviation of travel time	
Coefficient of variation (σ/μ)	Standard deviation divided by mean	
Buffer index (BI)	$\frac{\text{95th percentile time} - \hat{\mu}}{\hat{\sigma}}$	$\hat{\mu}$: estimated mean $\hat{\sigma}$: estimated standard deviation
Planning time index	$\frac{\text{95th percentile time}}{\text{free flow travel time}}$	
Skew statistic	$\frac{\text{90th percentile time} - \text{50th percentile time}}{\text{50th percentile time} - \text{10th percentile time}}$	
Congestion index	$\frac{\hat{\mu}}{\text{average free flow travel time}}$	
Percentage on time	$\frac{\text{trips} \mid \text{travel time} < 1.1\hat{\mu}}{\text{total trips}}$	
Delay related		
Frequency of running behind schedule	Self-explanatory	For transit
Lateness measure	Average delay (unexpected waiting time per trip)	For transit
Risk measure	Probability of delay of certain length	

independent, and then both mean and variance of travel time are additive, as shown in Equations 3.1 and 3.2:

$$\mu_r = \sum_{a \in r} \mu_a \tag{3.1}$$

$$\sigma_r^2 = \sum_{a \in r} \sigma_a^2 \tag{3.2}$$

where r is route, and a is link.

The independency assumption perhaps is problematic as link travel times are not independent if queue spillovers occur. If the travel times between links are perfectly correlated, then variance of travel time on routes is much higher than the simple algebra sum of variance of travel times on links.

Taylor (2009) proposed a route-based reliability measurement based on speed as shown in Equation 3.3.

$$R(r, t) = \frac{1.44}{\bar{V}_{rt}} \sqrt{\frac{\sum_d \left(V_{rtd} - \bar{V}_{rt}\right)^2}{N_{rt} - 1}} \tag{3.3}$$

where

$R(r, t)$: reliability metric;
r: route index;
t: time index;
d: day index;
V_{rtd}: average speed of all vehicles on route r departing at time t on day d;
$\bar{V}_{rt}$: average speed of all vehicles on route r departing at time t; and
N_{rt}: sample size of vehicles on route r departing at time t.

Taylor's equation can be conveniently used in a simulation environment. Speeds of all vehicles on each route with each departure time clock are known in the simulator, and thus the route reliability metric in Equation 3.3 can be trivially computed for both freeways and arterials.

3.2.3 Valuating Travel Time Reliability

Due to the two definitions of travel time reliability, there are two methods to value travel time reliability: the mean variance method and the schedule delay method.

3.2.3.1 Mean Variance Method

The mean variance method valuates travel time variability as shown in Equation 3.4:

$$\text{GC} = \text{VOTT} \cdot \mu + \text{VTTR} \cdot \sigma \tag{3.4}$$

where

GC: generalized cost;
VOTT: value of travel time; and
VTTR: value of travel time variability.

The user costs now possess two terms. One term is the usual cost of travel time measured by VOTT multiplied by the mean value of travel time μ, and the other term is the cost of travel time variability, measured by VTTR multiplied by the standard deviation of travel time σ.

VOTT is well calibrated and typically is known for most travel demand models in metropolitan areas, but VTTR is less known. In a more convenient way, practitioners use the concept of the reliability ratio (RR), which is the ratio of VTTR divided by VOTT, defined by Equation 3.5:

$$\text{RR} = \frac{\text{VTTR}}{\text{VOTT}} \tag{3.5}$$

If RR can be established and VOTT is known, then VTTR can be computed.

Several facts known for RR (Cambridge Systematics 2012) include the following:

- Past studies of reliability valuation for passenger travel have found a wide range of values, but more recent studies appear to be coalescing around an RR of 1.0 (Lam and Small 2001).
- Many non-U.S. countries have undertaken their own review of reliability valuation and have recommended specific values for VTTR and/or RR for use in economic analyses. They include
  - The Netherlands: 0.8 and −1.4 for personal auto and public transit, respectively
  - New Zealand: 0.8 for personal autos
  - Australia: 1.3 for personal autos
  - Sweden: 0.9 for all trip types
  - Canada: 1.0 for all trip types
- Use of a single (composite) RR in technical analyses may be misleading. The RR value may vary according to number of factors. Researchers have noted that just as for VOTT, VTTR can vary by a number of factors. SHRP 2 Projects C04 and L04 derived an expansive set of RR for combinations of trip type, income, and trip length. In general, the influences of these factors are
  - Trip type: the RR for the trip to work is higher than the trip from work or nonwork trips
  - Income: for the work trip, lower income groups have a higher RR
  - Trip length: for the work trip, RR decreases with trip distance
  - Freight: some evidence exists that both the VTTR and RR are higher than for passenger travel, but these values are highly dependent on the type of commodity.

3.2.3.2 Schedule Delay Method

In the schedule delay method, the utility of a trip is measured by Equation 3.6:

$$E(U) = \alpha \cdot E(T) + \beta \cdot E(\text{SDE}) + \gamma \cdot E(\text{SDL}) + \theta p_L \tag{3.6}$$

where

$E(U)$: expected value of disutility;
$E(T)$: expected value of trip travel time;
$E(\text{SDE})$: expected value of schedule delay earlier;
$E(\text{SDL})$: expected value of schedule delay late; and
p_L: probability of being late.

The stated-preference survey revealed that $\gamma > \beta > \alpha$.

If it is assumed that (1) the travel time distribution is independent of departure time, (2) the standardized distribution of trip duration Φ is constant, (3) $\theta = 0$, and (4) an agency can choose departure time to maximize the expected disutility, then optimal maximum expected utility is given by Equation 3.7:

$$E(U)_{\max} = \alpha\mu + (\beta + \gamma) \cdot H\left(\Phi, \frac{\beta}{\beta+\gamma}\right)\sigma \tag{3.7}$$

where $H\left(\Phi, \frac{\beta}{\beta+\gamma}\right)$ is the mean lateness factor depending on both the standardized travel time distribution and preference parameters of being late and earlier (Fosgerau and Karlstrom 2010). Note that $H\left(\Phi, \frac{\beta}{\beta+\gamma}\right)$ takes into account the skew of the travel time distribution. This result exhibits the connection between two methods of mean–variance and schedule delay, and the RR in theory is given by Equation 3.8:

$$\text{RR} = \frac{\beta+\gamma}{\alpha} H\left(\Phi, \frac{\beta}{\beta+\gamma}\right) \tag{3.8}$$

3.2.4 Predicting Travel Time Reliability

Mean travel time can be forecast by traffic assignment with the future-year data, but this is usually not the case for travel time variability. Existing practice and analytical methods described in the literature offer two methods to predict travel time variability: the statistical method and the simulation method.

3.2.4.1 Statistical Method

The statistical method assumes (and this assumption is partially supported by the data) that the standard deviation of travel time variability, or other similar reliability measurements [e.g., travel time index (Cambridge Systematics 2012)] could be interpreted as a function of mean of travel time (μ) or mean of travel time per mile (Northwestern University Transportation Center 2009). Several examples of regression models found in practice and the literature are summarized as follows:

- Dutch Study (Peer et al. 2009)

$$\sigma = \beta_1 \cdot (\mu - \text{FFT})^{\beta_2} + \left(\frac{v}{c}\right)^{\beta_3}$$

where FFT is free-flow time and v/c is the ratio of volume divided by capacity.

- Eliasson (2009)

$$\sigma = \text{const} \cdot \text{TT}^{1.2} \cdot \sqrt{\frac{\text{TT}}{\text{FFT}} - 1}$$

where
const: a constant parameter;
TT: travel time; and
FFT: free-flow travel time.

- Leeds Model (Vovsha 2009)

$$\frac{\sigma}{D} = 0.148 \cdot \left(\frac{\mu}{D}\right)^{1.781} \cdot \text{FFS}^{0.781} \cdot (D/1.6)^{-0.285}$$

where D is distance, and FFS is free-flow speed.

3.2.4.2 Simulation Method

The simulation approach is usually implemented with the Monte Carlo method in conjunction with traffic flow models (Clark and Watling 2005). Monte Carlo methods generate samples with known probability density functions, run simulations, and produce aggregate statistical results. If incidents, which are regarded as a major source of travel time variability, can be predicted using a hazard model, then the resultant travel time variability could be produced using a Monte Carlo method (Dong and Mahmassani 2011).

The simulation methods based on Monte Carlo are primarily seen in theoretical studies. These methods are seldom seen in practical applications, partly because (1) it is difficult to trace all possible sources that influence travel time reliability and difficult to validate the probability density function of those sources for future years, and (2) the approach is computationally expensive.

3.3 First Workshop: Early Stage Project Planning and Coordination

Two workshops were held in Portland, Oregon. These workshops served to engage local policy makers and obtain feedback with regard to the outcomes of this research project.

The objective of the first workshop was to introduce key stakeholders of the Southwest Corridor project to the research agenda. Items discussed included the goals, scope, and role of the research as it related to the corridor project, the methods previously used to measure reliability, and the research operation plan.

The first workshop took place on July 9, 2013. In addition to the project team, which included Portland Metro, University of Arizona, RST International Inc., and the Transportation Research Board (TRB) supervisory team, the technical advisory committee for the Southwest Corridor study also attended the workshop. The technical advisory committee membership included the Oregon Department of Transportation (DOT), City of Portland, City of Tigard, City of Sherwood, Washington County, TriMet, and other stakeholders.

Workshop participants were first introduced to the project objectives, scope, and tasks in order for them to understand their role in this project and to set their expectations properly. After lively discussions on the notion of reliability and the reliability measures, participants engaged in a hands-on stated-preference exercise as part of the workshop. This exercise, which is discussed in Section 3.3.1, aimed to engage workshop participants in an active cognitive process to elucidate their collective assessment of the value of travel time reliability (VTTR). The exercise was a simple binary choice of two alternate routes with varying travel time and reliability characteristics. This method was inspired by a recent Dutch study (Significance et al. 2013).

The 20 workshop attendees included the following:

- Project supervisory team—TRB
- Project team—Portland Metro
- Policy team
  - TriMet
  - Washington County
  - City of Tigard
  - Oregon DOT
  - City of Sherwood
  - City of Portland
- Project team—University of Arizona
- Project team (in kind)—University of Queensland (tentative)
- Oregon DOT Transportation Planning and Analysis Unit observer.

3.3.1 VTTR Estimation Method and Decision Context

The high-level concept proposed by the research team to estimate the utility function is given by the following equation. The binary logit model was intended to represent the choice decision of interest. The utility function set up for this study is

$$U = \alpha_0 + \alpha_1 \text{TT} + \alpha_2 \text{TR}$$

where
TT = average route travel time;
TR = standard deviation of the route travel time observations; and
α_x = alternative specific constant or attribute coefficients.

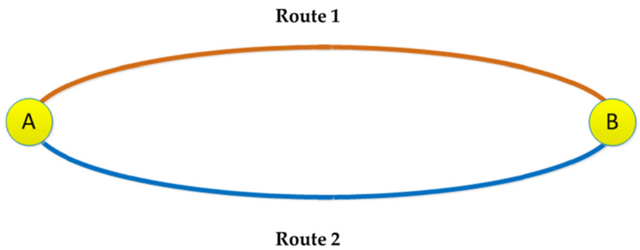


Figure 3.1. Illustration of route choice exercise.

RR can then be calculated as $\frac{\alpha_1}{\alpha_2}$ because RR is calculated as the ratio of VOTT to VTTR, and both VOTT and VTTR are calculated with respect to a cost variable, which is intentionally left out in this utility function. Mathematically, the coefficient of the cost term is canceled out when calculating RR. For a general-purpose survey the actual number of variables in the utility function would need to be more comprehensive, but because the purpose of this method is to obtain the inter-attribute relationship RR, then this utility function, with a limited number of generic variables, would be sufficient barring that the overall goodness of fit may not be as high as if other relevant variables were to be included.

The workshop exercise applied a simple binary route choice problem as the decision context setup. Route 1 was indicated in red, and Route 2 was in blue (Figure 3.1). Such a color scheme was kept consistent throughout the engagement process to ensure consistency in cognition.

3.3.2 Stated-Preference Problem Preparation

The exercise technology was based on a classroom interactive learning module powered by Turning Technologies (Turning Technologies 2014). The technology has often been used for real-time in situ assessment of audience opinions by asking selected questions at the end of each module. Several types of questions can be displayed, but the most commonly used type of question is the multiple choice question. The questions were set up using a procedure from a software package provided by Turning Technology that embeds a specialized function into Microsoft PowerPoint.

Figure 3.2 is an example question prepared in a Turning Technology embedded PowerPoint slide. One can see that two route options are presented. Each route is given start time information and five past travel time observations. Each of the past experience observations is represented by both travel time and arrival time (by taking arrival time plus the start time). The five observations allowed respondents to assess both travel time average and variance simultaneously. The setup of the questions was inspired by a recently published travel time reliability report (Significance et al. 2013).

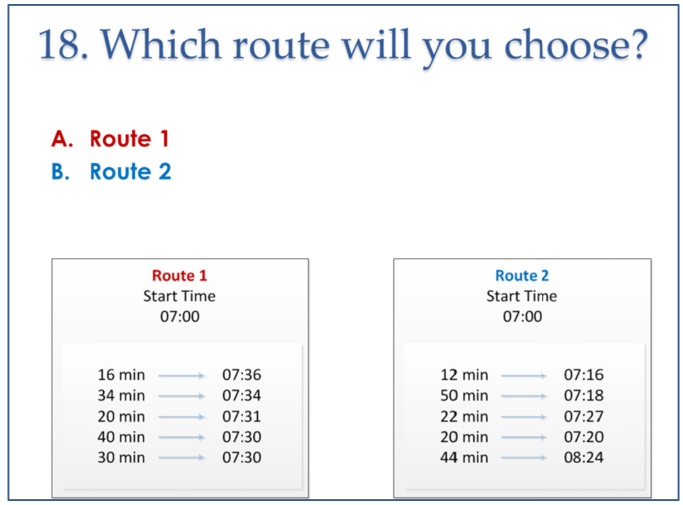


Figure 3.2. Example route choice question.

A total of 20 questions were generated for this workshop. Twenty questions were chosen with the aim of collecting sufficient data without tiring participants with an excessive number of questions. In each question, the attribute values of both routes were generated by a random process following a log-normal distribution with a user-specified mean and standard deviation input. Minor manual adjustments were performed to fine-tune the variability and average. In the example shown in Figure 3.2, Route 1 was given a higher mean and lower standard deviation than the same values given for Route 2. The workshop participants were provided with a clicker and needed only to press the appropriate number button on the clicker when asked to make a choice for the type of question illustrated in Figure 3.2. A wireless receiver was inserted into the USB port of the main computer to take signal inputs from all clickers, and polling was closed when all participants had entered their answer, usually in about 10 to 15 seconds.

3.3.2.1 Model Estimation Results

Once the polling was closed, the PowerPoint immediately displayed the aggregated choices by all participants, as shown in Figure 3.3. In this example, 21% of the participants chose Route 1 and 79% choose Route 2.

One of the team members asked participants to discuss the reasons and considerations that led them to make a certain choice. Such a process provided the following advantages:

- Participants were quickly engaged in lively discussions.
- The instant feedback mechanism allowed them to review their personal choice in comparison to choices made by peers.
- The variability of choices could be observed by the choice breakdown.

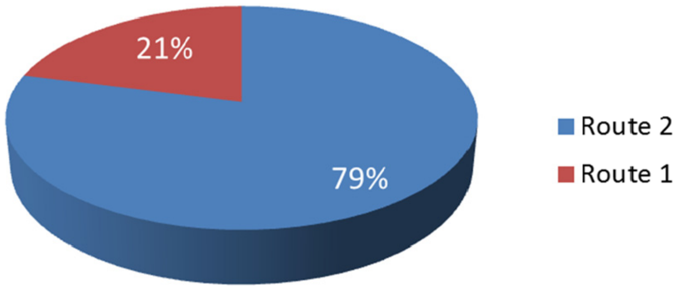


Figure 3.3. Aggregated route choice decision for Question 18 (Question 18 is shown in Figure 3.2).

After the workshop, the research team exported and processed the collected data into the format needed for the model estimation software. The study initially used the easy logit model developed by Frank Koppelman, an emeritus Northwestern University professor in transportation econometrics. Later, the model estimation tasks were performed using R. The model estimation results in Table 3.2 indicated a desirable goodness of fit, with an adjusted Rho square valued at 0.34. The *t*-statistics for both generic variables, travel time (average) and travel time reliability (measured as standard deviation), were significant at –6.85 and –4.39, respectively. The sign of the coefficients is negative, which is intuitive.

Table 3.2. Multinomial Logit Model Estimation Results

Parameter or Statistic	Estimated Value	*t*-Statistic
Generic Parameters		
Travel time (average)	–0.1629	–6.8491
Travel time reliability (standard deviation)	–0.1243	–4.3939
Alternative Specific Parameters		
Constant	–0.7344	–3.7392
Model Statistics		
Log likelihood at zero	–263.3959	
Log likelihood at constants	–215.8566	
Log likelihood at convergence	–138.6865	
Rho squared w.r.t. zero	0. 4735	
Rho squared w.r.t. constants	0.3575	
Adjusted rho squared w.r.t. zero	0.4621	
Adjusted rho squared w.r.t. constants	0.3466	
Number of cases	380	
Number of iterations	18	

Note: w.r.t. = with respect to.

The resulting RR is 0.76, which is consistent with that reported in the literature; recall that the recent Dutch model reported a general value of 0.6 (Significance et al. 2013), as well as the following:

- The Netherlands finding (passenger car)
  - Home-to-work trip (€3.75 versus €9.25) = 0.4
  - Business trip (€30.0 versus €26.5) = 1.1
  - Average (€5.75 versus €9.0) = 0.6; and
- The Netherlands finding (transit)
  - Home-to-work trip (€3.25 versus €7.75) = 0.4
  - Business trip (€21.75 versus 19.0€) = 1.1
  - Average (€3.75 versus €6.75) = 0.6

Despite a large body of research on the value of reliability, obtaining a value that is plausible and acceptable and permitted by project scope was a challenging task. Considering the tight schedule to accomplish all the required project tasks, the research team employed a cost-effective method and a locally reasonable approach to obtain the local value. This local value was primarily used for the proof-of-concept, policy-maker engagement purpose of this project, rather than for a generalized, actual policy-making application. It was jointly agreed by the research team and the policy group that a small-scale, stated-preference–based route choice survey would be used for the specific purpose of this research. The value obtained from the proposed method will not be sufficient for a general purpose. Discussions on how to extend the proposed method to a generalized context will be discussed.

3.4 General Concepts for Travel Time Reliability Measure and Value of Reliability

3.4.1 Determining a Travel Time Reliability Measure

The L35A research team and the Metro policy group agreed to select standard deviation as the measure of reliability in this research due to the following considerations:

1. Participants at the first workshop expressed a general consensus that some form of expression of dispersion is an acceptable reliability measure. Although multiple measures exist in reality under different decision contexts, only one measure could be used for this study, and dispersion was considered adequate.
2. Using standard deviation allowed the model estimation results to be consistent with results in the literature, particularly the latest comprehensive Dutch study concerning travel time reliability (Significance et al. 2013).

3. Dispersion is consistent and measurable using the proposed SHRP 2 L03 approach (Cambridge Systematics 2013a) with DynusT and FAST-TrIPs.

3.4.2 Determination of Travel Time Reliability

Without overextending the scientific merit of using a simple interactive tool like the clicker, the workshop exercise did provide an effective situational engagement experience for participants, and it also produced desirable model estimation outcomes. After extensive discussion among L35A research team members and with TRB, the L35A research team decided to refine the questions and re-conduct a similar exercise with internal staff selected by Metro. The purposes of this second exercise were to

1. Refine the attribute values for questions.
2. Incorporate transit reliability into question sets.
3. Introduce trip purpose into the question set up so that responses were more contextual and became more consistent with the literature, which would indicate that the value of reliability could be highly related to trip purpose.

This procedure allowed the research team to reasonably estimate the RR for both automobile and transit modes for the purpose of this project despite various limitations. RR also enabled estimation of the VTTR through the following rationale:

$$\text{Reliability Ratio (RR)} = \frac{\text{VTTR}}{\text{VOTT}}$$

therefore

$$\text{VTTR} = \text{RR} \times \text{VOTT}$$

RR is estimated as described above. The VOTT is known in the current Metro travel demand model (TDM) and has been established by Metro through past effort so VOTT should not be changed by this survey. Instead, the survey focused on estimating the relativity of VOTT and VTTR; once this relationship is established, VTTR can be reasonably inferred.

This method of estimating VTTR was considered acceptable by the policy group to avoid having to launch a new travel survey. This method is arguably theoretically sound, because prior studies have found both travel time and travel time reliability to be statistically significant when included in the same utility function, meaning that these two attributes are not highly correlated statistically. Adding the travel time reliability variable to the Metro utility function will not statistically change the coefficient for the travel time term. If these factors were to change, they would probably be scaled with a scaling factor, and the relative relationship would remain similar. Because RR was obtained in this study through an adequate stated-preference data collection procedure, the obtained RR was deemed reasonable, and thus deriving the value of travel time reliability by using the product of RR and the value of travel time was also considered reasonable.

It is not the VTTR but instead the value of RR that is used in subsequent scenario analysis. More details on how the estimation results were used are presented in Chapter 5.

3.4.3 Validity of Reliability Ratio due to Limited Sample Size

The L35A research team also explored the possibility of extending the stated-preference survey for obtaining the RR by using a large external panel (20,000 members) maintained by Metro. This active panel has provided valuable inputs to various policies contemplated by Metro in the past. To perform a similar survey with this panel was technologically feasible, but it was not within the scope of this project. Such a large survey would have required additional time and resources plus an institutional review board approval process and hence was deemed high risk from a project management standpoint. Nonetheless, this concept is worth exploring further.

Without collecting regionwide data, the external validity of the estimated RR may be of concern if this value were to be applied to a real-world project selection process. The research team emphasized the research nature of L35A to the Metro decision-maker panel, and realistic expectations were established.

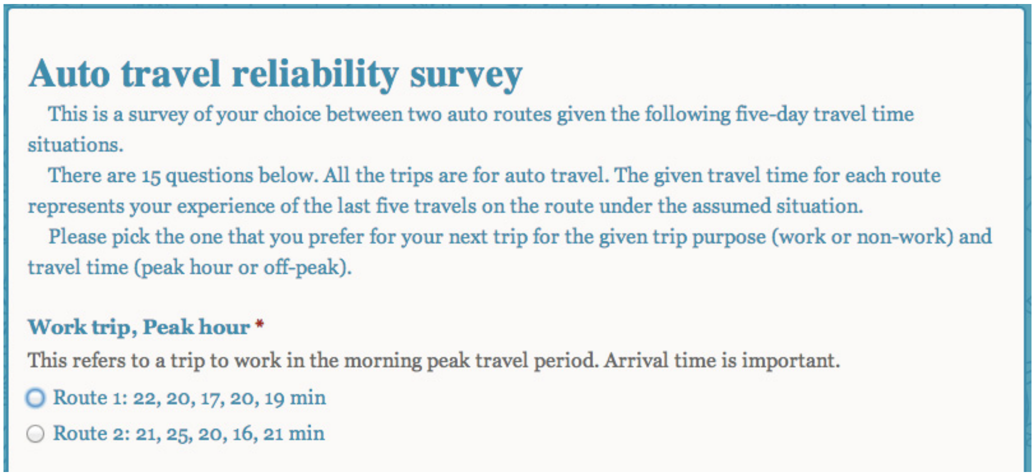
A second round of online exercises was devised and delivered to the Metro staff in early October 2013. Details on this modification of the questionnaire design and the results of this exercise are included in the next section.

3.5 Survey for Estimating Reliability Ratio

3.5.1 Questionnaire Design and Instruments

This questionnaire for the online survey maintained the same format as for the first workshop by providing two route options, each with five experienced travel time values. The options were improved by identifying the differences by trip purpose and time of day and providing the transit situation. With fewer than 80 participants expected and with two variables to be estimated, five questions for each type of trip purpose situation were determined to provide a sufficient sample in model estimation.

To incorporate RR into the Metro model further, the trip purpose and time-of-day situations were designed to be consistent with the existing four trip purposes in the Metro model. Three situations combining purpose and time of day



Auto travel reliability survey

This is a survey of your choice between two auto routes given the following five-day travel time situations.

There are 15 questions below. All the trips are for auto travel. The given travel time for each route represents your experience of the last five travels on the route under the assumed situation.

Please pick the one that you prefer for your next trip for the given trip purpose (work or non-work) and travel time (peak hour or off-peak).

Work trip, Peak hour *

This refers to a trip to work in the morning peak travel period. Arrival time is important.

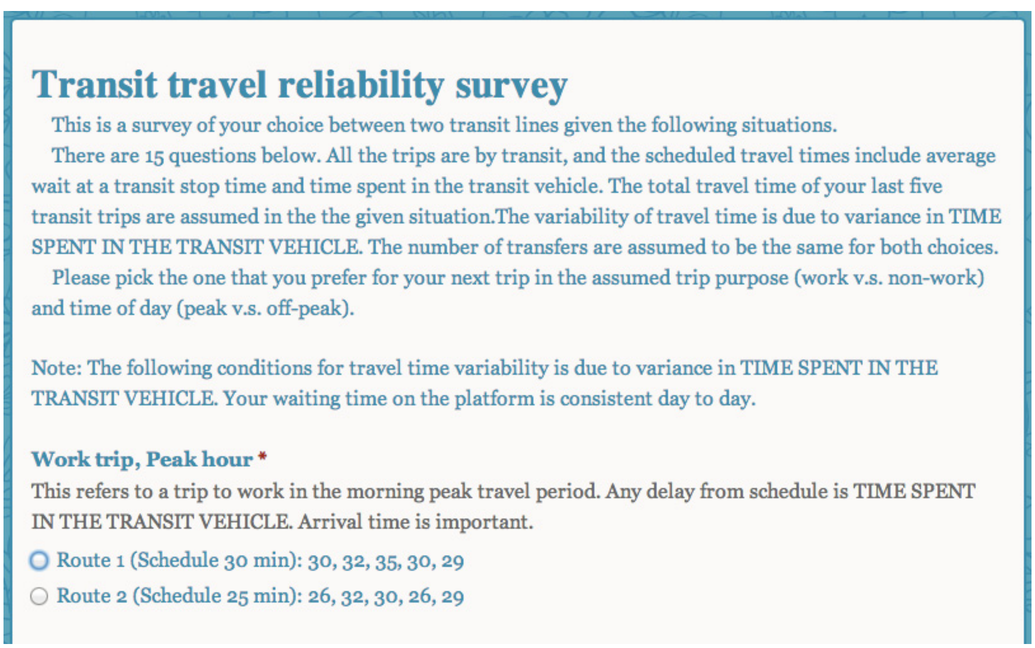
- Route 1: 22, 20, 17, 20, 19 min
- Route 2: 21, 25, 20, 16, 21 min

Figure 3.4. Survey question snapshot for auto travel reliability.

(work, peak hour; nonwork, peak hour; and off-peak hour) were chosen to simplify the model estimation and avoid a long questionnaire. Therefore, 15 questions needed to be provided to each participant.

The questionnaire was designed with both an automobile trip survey and a transit trip survey. Each respondent could answer either one according to his or her major travel mode or both surveys if automobile and transit were both commonly used. The travel time values in each option were randomly generated given the travel time and standard deviation. The travel time for the automobile survey ranged from 15 to 50 min, and the standard deviation ranged from 2 to 20 min. If we consider the transit schedule and on-time performance, the travel time for the transit survey ranged from 25 to 50 min, and the standard deviation ranged from 0 to 7 min. To provide more diversity in the survey, two questionnaires were finally designed with different travel time options for each question. In the transit survey, one questionnaire emphasized that "travel time variability is due to variance in WAITING TIME AT THE TRANSIT STOP," and another questionnaire emphasized that "travel time variability is due to variance in TIME SPENT IN THE TRANSIT VEHICLE."

Example snapshots of the questionnaires are shown in Figures 3.4 and 3.5.



Transit travel reliability survey

This is a survey of your choice between two transit lines given the following situations.

There are 15 questions below. All the trips are by transit, and the scheduled travel times include average wait at a transit stop time and time spent in the transit vehicle. The total travel time of your last five transit trips are assumed in the the given situation.The variability of travel time is due to variance in TIME SPENT IN THE TRANSIT VEHICLE. The number of transfers are assumed to be the same for both choices.

Please pick the one that you prefer for your next trip in the assumed trip purpose (work v.s. non-work) and time of day (peak v.s. off-peak).

Note: The following conditions for travel time variability is due to variance in TIME SPENT IN THE TRANSIT VEHICLE. Your waiting time on the platform is consistent day to day.

Work trip, Peak hour *

This refers to a trip to work in the morning peak travel period. Any delay from schedule is TIME SPENT IN THE TRANSIT VEHICLE. Arrival time is important.

- Route 1 (Schedule 30 min): 30, 32, 35, 30, 29
- Route 2 (Schedule 25 min): 26, 32, 30, 26, 29

Figure 3.5. Survey question snapshot for transit travel reliability.

3.5.2 Model Estimation Results

The online survey was active from September 20 to 27, 2013. In total, 36 members of the Metro staff responded to the questionnaire; 34 responses to the automobile survey and 24 responses to the transit survey were completed. The average travel times were 28 min for the automobile survey and 36 min for the transit survey; the average standard deviations were 5.6 and 2.8 min, respectively, for automobile and transit. A distribution of travel time and standard deviation is shown in Figure 3.6.

The model, which had the same formulation as for the workshop, was estimated in statistical software R. Because the same respondent was asked multiple questions, it was natural to consider using the mixed logit model to account for taste variation. After testing both the mixed logit and multinomial logit models, we found that the mixed logit model did not appear to be superior to the multinomial logit model, and multinomial logit–estimated RRs were more comparable to RR values reported in the literature. Multinomial logit model results were used in the subsequent steps of the project.

The estimates in the mixed logit model appeared not to be significant for travel time and standard deviation for all Transit and Auto_peakhour_nonwork trips.

Only coefficients for two variables, Auto_peakhour_work and Auto_offpeak trips, appeared to be significant. Comparing the log likelihood, the random parameter for travel time and reliability with mean and standard deviation did not improve the model goodness of fit with more parameters.

RRs for the two models are shown in Table 3.3. There is no telling which one is "better," but the multinomial logit results appeared to be more comparable to previous studies and were chosen for the case study in this project.

The coefficients of the travel time and travel time reliability terms were estimated from the data, and RR was calculated as the coefficient of travel time reliability divided by the coefficients of travel time, as shown in Table 3.4; model estimation results are shown in Table 3.5. There is a decreasing trend by situation from work peak to off peak, implying the strong importance of reliability during peak hours, especially for work-related trips. Transit riders in this survey appeared to have a higher evaluation of reliability than automobile users. This difference can be interpreted as transit riders' expectation of more reliable service by transit and their low tolerance for delay if they choose transit instead of driving. This interpretation is likely for Portland, which is known to have reliable transit service. For other regions, if the highway system is (or becomes) more reliable than the transit system, a similar survey could find that highway users have a higher VTTR than transit riders.

A low tolerance could also be attributed to a higher schedule delay penalty, as transit users could be counting on transit's on-time arrival for work and meetings and may have budgeted a smaller travel time buffer. The waiting area and weather conditions (such as rainy days in Portland) at the bus stop may also contribute to increased VTTR.

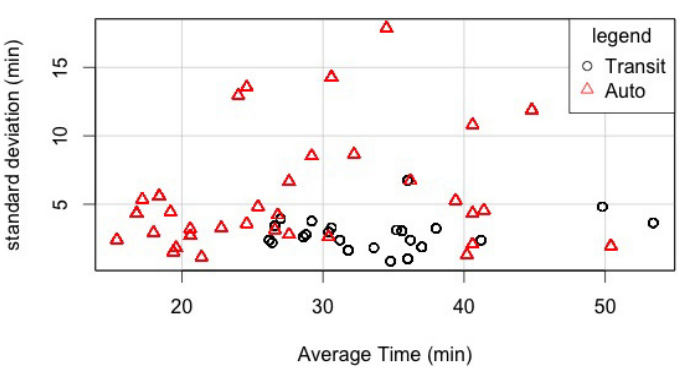


Figure 3.6. Distribution of average and standard deviation of travel time in the online survey questions.

Table 3.3. Reliability Ratio Estimates with Multinomial Logit and Mixed Logit Models

Trip Purpose and Time of Day	Multinomial Logit	Mixed Logit
Transit work peak hour	1.439	4.094
Transit work off peak	1.431	1.624
Transit other	0.831	0.751
Auto work peak hour	0.681	1.257
Auto work off peak	0.343	0.169
Auto other	0.417	0.257

3.5.3 Comparison with the Literature

The L35A research team found that, in spite of its simplified process, the RR obtained for automobile travel was consistent with values summarized in the literature, particularly in the Dutch study (Significance et al. 2013). The RR values for three trip purposes and for overall automobile trips were

Table 3.4. Reliability Ratios for Automobile and Transit by Trip Purpose and Time of Day

Trip Purpose and Time of Day	Automobile	Transit
Work, peak hour	0.83	1.55
Nonwork, peak hour	0.35	1.51
Off peak	0.27	0.76
Overall	0.45	1.06

Table 3.5. Summary of Model Estimation Results

System	Work, Peak Hour		Nonwork, Peak Hour		Off Peak		Overall	
	Estimate	*t*-Statistic	Estimate	*t*-Statistic	Estimate	*t*-Statistic	Estimate	*t*-Statistic
Automobile								
Constant	–0.480	–1.718	–0.134	–0.753	–0.366	–0.892	–0.049	–0.458
Travel time	–0.337	–5.710	–0.395	–4.412	–0.413	–5.244	–0.391	–9.750
Travel time reliability	–0.280	–5.130	–0.140	–2.667	–0.111	–1.120	–0.177	–6.555
Adjusted ρ^2		0.3756		0.1408		0.3338		0.2705
Transit								
Constant	–0.155	–0.035	–0.255	–0.890	0.433	0.974	–0.013	–0.077
Travel time	–0.620	–4.214	–0.434	–3.292	–0.860	–5.281	–0.719	–10.454
Travel time reliability	–0.963	–2.894	–0.657	–2.797	–0.649	–3.110	–0.760	–7.125
Adjusted ρ^2		0.3959		0.1015		0.4472		0.4151

within the major range of 0.3 to 0.9 reported by that study, as shown in Table 3.6.

The RR value for transit in the Dutch study (Significance et al. 2013) was higher than the expectation from the literature. The highest value in the literature (shown in Table 3.7), 1.4, is from the expert workshop of 2004 in the Netherlands.

Table 3.6. Snapshot of Reliability Ratio for Automobile Travel

Study	Country	RR
MVA (1996)	United Kingdom	0.36–0.78
Copley et al. (2002)	United Kingdom	Pilot survey: 1.3
Hensher (2007)	Australia	0.30–0.95
Eliasson (2004)	Sweden	NCHRP 431: 0.80–1.10 SHRP 2 C04: 0.40–0.90
Mahmassani (2011)	United States	0.8
Significance et al. (2013)	The Netherlands	Commuting: 0.4 Business: 1.1 Other: 0.6

Source: Significance et al. (2013).

Table 3.7. Snapshot of Reliability Ratio for Transit Travel

Study	Country	RR
MVA (2000)	Norway	Short trips: 0.69 Long trips: 0.42
Ramjerdi et al. (2010)	The Netherlands	1.4
Significance et al. (2013)	The Netherlands	Commuting: 0.4 Business: 1.1 Other: 0.6

Source: Significance et al. (2013).

In the present study, the two values for work peak and nonwork peak were both above 1.5 (as shown in Table 3.4); that is, the values were much higher than the RR for off-peak hours. Therefore, transit riders care about travel time reliability much more during peak hour travel than off-peak travel.

3.6 Reliability Measure Calculation

3.6.1 Modeling Reliability Measures for Automobiles

As an input, reliability affects travelers' decisions about trip making and choices of destination, mode, and route. It can be thought of as an extra impedance to travel over and above the average travel time generally used in demand models. Current models' definition of average travel time is based solely on recurrent (demand and capacity) conditions. Considering reliability means nonrecurrent sources of congestion must be factored into the process.

The concept of "extra impedance to travel over and above the average travel time" is probably the best way to incorporate reliability into the modeling structure as an input. In its application of this approach, SHRP 2 Project L03 (Cambridge Systematics 2013a) characterized the impedance on a link as a generalized cost function that included both the average travel time and its standard deviation (which was used as the indicator of reliability). As discussed below, L03 functions were used in the present study to establish the total link impedance for trip distribution and assignment purposes.

In order to apply this model framework, a method must exist for predicting the standard deviation of travel time. SHRP 2 Project L03 developed such methods from empirical data by using the travel time index (TTI) as the dependent variable. TTI is defined as the ratio of the actual travel time to the travel time under free-flow conditions, as shown by Equation 3.9:

$$\text{TTI} = \text{actual travel time/free flow travel time} \tag{3.9}$$

If actual travel time is a random variable, then TTI is a random variable. If the relationship between TTI and actual travel time is a linear relationship with a factor 1/(free-flow travel time), then the relationship between TTI and the standard deviation of travel time is also a linear relationship.

Equation 3.9 is a generalized equation for TTI. The following discussion defines several versions of TTI for use in reliability estimation.

In addition to the TTI calculation, free-flow speed is required for estimating delay. In DynusT networks, each link is specified with a free-flow speed, so such a value can readily be used for TTI calculation.

Because of limitations of the procedures being adapted, the smallest time period for which travel time performance measures could be calculated was 1 hour. The same computation would apply for a different time period, such as 30 min, but with a different aggregation and average period. From SHRP 2 Project L03, the following measures for TTI have been proposed (Equations 3.10 through 3.18):

- Performance measures for urban freeways

$$95\text{th \%ile TTI} = 1 + 3.6700 * \ln(\text{MeanTTI}) \tag{3.10}$$

$$90\text{th \%ile TTI} = 1 + 2.7809 * \ln(\text{MeanTTI}) \tag{3.11}$$

$$80\text{th \%ile TTI} = 1 + 2.1406 * \ln(\text{MeanTTI}) \tag{3.12}$$

$$\text{MedianTTI} = \text{MeanTTI}0.8601 \tag{3.13}$$

$$\text{StdDevTTI} = 0.71 * (\text{MeanTTI} - 1)^{0.56} \tag{3.14}$$

- Performance measures for signalized arterials

$$95\text{th \%ile TTI} = 1 + 2.6930 * \ln(\text{MeanTTI}) \tag{3.15}$$

$$80\text{th \%ile TTI} = 1 + 1.8095 * \ln(\text{MeanTTI}) \tag{3.16}$$

$$\text{MedianTTI} = \text{MeanTTI} * 0.9149 \tag{3.17}$$

$$\text{StdDevTTI} = 0.3692 * (\text{MeanTTI} - 1)^{0.3947} \tag{3.18}$$

Mean TTI is the grand (overall) mean. Because mean TTI was developed from continuous detector data, it includes all the possible influences on congestion (e.g., incidents and inclement weather). Currently, DynusT provides an estimate only of the recurrent (bottleneck only) congestion that is related to volume and capacity. Therefore, a mean TTI based on current DynusT output cannot be used. The following method should be used to estimate the true mean TTI. The method uses the DynusT output to estimate recurrent delay and a sketch-planning method to estimate incident delay, and then combines these two measures. The steps are as follows:

1. Compute the recurrent delay for each link in hours per mile from the simulation model (Equation 3.19):

$$\text{RecurringDelay} = \text{AverageTravelRate} - (1/\text{FreeFlowSpeed}) \tag{3.19}$$

   where AverageTravelRate is the inverse of the DynusT speed.
2. Compute the delay due to incidents (IncidentDelay) in hours per mile for a one-hour period by using the lookup table from the *ITS Deployment Analysis System (IDAS) User's Manual* (Cambridge Systematics 2009). This lookup table requires the v/c ratio and the number of lanes and provides the "base incident delay." The IDAS table is reproduced in Table 3.8 below.

***Table 3.8.* IDAS *Delay Lookup Table:* IDAS *Delay Rates for One-Hour Peak*[a]**

Volume/Capacity Ratio	Number of Lanes		
	2	3	4+
0.05	3.44E-08	1.44E-09	4.39E-12
0.1	5.24E-07	4.63E-08	5.82E-10
0.15	2.58E-06	3.53E-07	1.01E-08
0.2	7.99E-06	1.49E-06	7.71E-08
0.25	1.92E-05	4.57E-06	3.72E-07
0.3	3.93E-05	1.14E-05	1.34E-06
0.35	7.20E-05	2.46E-05	3.99E-06
0.4	0.000122	4.81E-05	1.02E-05
0.45	0.000193	8.68E-05	2.34E-05
0.5	0.000293	0.000147	4.93E-05
0.55	0.000426	0.000237	9.65E-05
0.6	0.0006	0.000367	0.000178
0.65	0.000825	0.000548	0.000313
0.7	0.001117	0.000798	0.000528
0.75	0.001511	0.001142	0.00086
0.8	0.002093	0.001637	0.00136
0.85	0.003092	0.002438	0.002115
0.9	0.005095	0.004008	0.003348
0.95	0.009547	0.007712	0.005922
≥ 1.0	0.01986	0.01744	0.01368

[a] Vehicle hour of incident delay per vehicle mile.

If incident management programs have been added as a strategy *or* if a strategy lowers the incident rate (i.e., frequency of occurrence), then the "after" delay is calculated as shown by Equation 3.20:

$$D_a = D_u * (1 - R_f) * (1 - R_d)^2 \tag{3.20}$$

where

D_a = adjusted delay (hours of delay per mile);

D_u = unadjusted (base) delay (hours of delay per mile from the incident rate tables);

R_f = reduction in incident frequency expressed as a fraction (with $R_f = 0$ meaning no reduction, and $R_f = 0.30$ meaning a 30% reduction in incident frequency); and

R_d = reduction in incident duration expressed as a fraction (with $R_d = 0$ meaning no reduction, and $R_d = 0.30$ meaning a 30% reduction in incident duration).

Changes in incident frequency are most commonly affected by strategies that decrease crash rates. However, as crashes are only about 20% of total incidents, a 30% reduction in crash rates alone would reduce overall incident rates by $(0.30 \times 0.20) = 0.06$.

3. Compute the overall mean TTI, which includes the effects of recurrent and incident delay.

Equation 3.9 (TTI = ActualTravelTime/FreeFlowTravelTime) is a general equation for TTI. TTI can also be computed in the following way:

FreeFlowSpeed/ActualSpeed

To be able to use Equations 3.10 through 3.18, we need an estimate of the overall mean TTI from a distribution of TTIs (which are simply converted travel times). The overall mean TTI includes all sources of congestion because the equations were based on a year of data at each location. For simplicity, we assume that the mean TTI has two components: a recurrent mean (from DynusT) and an incident mean (from *IDAS*). In order to use the *IDAS* numbers, which are in terms of delay, we need to convert everything into delay and then reconvert to TTI.

Rewriting Equation 3.20, we have Equations 3.21A and 3.21B:

$$\text{MeanTTI} = \text{MeanTravelRate}/\text{FreeFlowTravelRate} \tag{3.21A}$$

$$\text{MeanTTI} = \frac{v_f}{v} = \frac{t}{t_f} = \frac{d/v}{d/v_f} = \frac{1/v}{1/v_f} \tag{3.21B}$$

From $\text{MeanTTI} = \frac{t}{t_f}$, $\text{MeanTTI} = \frac{t}{t_f} = \frac{t_f + \theta}{t_f}$ is obtained, where θ is the total delay (in hours), defined as the additional travel time on top of the free-flow travel time, which is the sum of recurrent delay θ_r and incident-induced delay θ_i; that is, $\theta = \theta_r + \theta_i$.

Consequently,

$$\text{MeanTTI} = \frac{t}{t_f} = \frac{t_f + \theta}{t_f} = 1 + \frac{\theta}{t_f} = 1 + \frac{\theta_r + \theta_i}{t_f} = \frac{\left[\frac{1}{v} + \theta_i\right]}{\frac{1}{v_f}}$$

The final equation becomes

$$\text{MeanTTI} = \frac{\left[\frac{1}{v} + \theta_i\right]}{\frac{1}{v_f}}$$

This essentially means that MeanTTI is the ratio of the sum of the recurrent congestion-induced travel rate and the incident-induced travel rate to the free-flow travel rate.

The term θ_i is the delay due to incidents (IncidentDelay) and is proposed using the IDAS table (Table 3.8), which estimates the vehicle hour of incident delay per vehicle mile based on the v/c ratio for a 2-lane facility, a 3-lane facility, and a 4+-lane facility.

Because the L03 equations predict TTI, the travel time can be computed as given by Equation 3.22:

$$\text{Travel Time} = \text{TTI} * \text{FreeFlowSpeed} \tag{3.22}$$

Small et al. (2005) defined unreliability as the difference between the 80th and 50th percentile travel times and found the value of unreliability to be approximately equal to the value of travel time. Based on this result, Equation 3.23 can be applied to calculate link travel time equivalents (TTEs) for a trip:

$$\text{TTE} = \text{MTT} + a * (80\text{th}\%\text{TTI} - 50\text{th}\%\text{TTI}) \tag{3.23}$$

where

TTE = link travel time equivalent;

MTT = mean travel time (min);

a = reliability ratio (using the value obtained from Metro staff survey);

80%TTI = 80th percentile TTI (min); and

50%TTI = 50th percentile TTI (min).

Mean travel time and 80th and 50th percentile TTIs were computed with the above equations. Based on currently available information, we recommend a value of 0.8 for a (the reliability ratio), but this value may be revised based on future research.

TTE is then used as a replacement for the average travel time in the feedback loop to the TDM. TTE is basically an inflated value of travel time over the average that accounts for how travelers value reliability. How the TDM, which was calibrated using average travel time, will behave with this inflated travel time value is unknown and was the subject of testing in this project.

3.6.2 Modeling Reliability Measures for Transit

Modeling reliability in the transit networks focuses on measuring travel time reliability and on using that measurement in the assignment model. We have added a submodel to the existing transit assignment model to estimate the variation in transit travel time and to capture its effect on transit riders' behavior. The added contributions of this effort compared to all prior efforts, including those in SHRP 2 C10B, were (1) to develop such a model for schedule-based transit networks by using the multimodal assignment model and (2) to use the method on the transit assignment model and the feedback to the other parts of the demand model.

In the first step, a general formulation for a transit TTI was proposed to capture the causes and effects of travel time variability. The model separates various sources of "excess" travel time, and based on these additional times, defines TTI. Additional delays imposed on the transit vehicles and thus on the passengers can be categorized into traffic delay, dwell time, holding time (in schedule-based networks), and incidental delay. Using the proposed TTI, different index values may be calculated for similar routes if they operate differently. The advantage of the proposed formulation is that, unlike methods in previous studies, it can accommodate both frequency-based and schedule-based routes. Transit users plan their trips according to the information they receive from transit operators in the form of published schedules, route headways, trip planner advice, and so forth. Therefore, their expectations of travel time may differ in frequency-based versus schedule-based systems. The TTI for a transit route segment is calculated through the dynamic multimodal assignment model. The transit assignment model will calculate the delay due to dwell time, and integration with the dynamic traffic assignment (DTA) model will help in estimating the traffic congestion and the holding time delay.

Transit TTI and TTE in schedule-based systems can be expressed as shown in the following equations:

$$\text{TTI} = \frac{\text{Mean Travel Time}}{\text{Scheduled Travel Time}}$$

$$\text{TTE} = \text{Mean Travel Time} + \propto_t \text{Reliability Time}$$

The proposed TTI is then used to calculate the mean travel time, travel time percentiles, and the TTE (t_E), similar to the calculation for the automobile network. This information is also used to estimate the distribution of vehicle arrival and departure times at each stop. The impact of transit reliability is considered in relation to the two major components of passenger travel time. The first component is in-vehicle travel time, which is modeled by TTE; that is, t_E, which is calculated by adding a travel time buffer to the mean travel time, is used by transit users in their decision-making process. The t_E is calculated based on the 80th percentile travel time in conjunction with the mean travel time (Van Oort 2011) by using a formula similar to the one used in the automobile network. However, the travel time RR may be different in automobile and transit networks. The second component of travel time affected by transit system reliability is the waiting time. To account for the vehicles' departure time variation (Hickman 2001), passengers may plan to arrive earlier than the expected vehicle departure time at the stop to minimize their chance of missing the vehicle. The buffer time used for the waiting time is typically based on the 95th percentile of the headway (Van Oort 2011), meaning that there will be little chance of missing the transit vehicle. As a new feature to add to the existing transit assignment model, a submodel was developed to model passenger incidence at the boarding stops. Based on the expected value and variation of the vehicle departures, the passenger incidence submodel can define three types of passenger arrival behavior, as well as their proportion among the total demand: random, coordinated with schedule, and coincidentally on time (Julliffe and Hutchinson 1975). The proposed assignment is achieved using the modified path algorithm in the transit assignment model. In the results, the impact of travel time reliability is captured on each individual passenger's decision, and the reliability of the transit network can be evaluated at different levels of aggregation, such as a route, a corridor, an O-D pair, or the whole network.

- In-vehicle travel time reliability

  $$\text{Reliability Time} = \text{80th\% travel time} - \text{50th\% travel time}$$

- Waiting time reliability with schedule-dependent passengers

  $$\text{Wait Time} = \text{95th\% Headway} - \text{Mean Headway}$$

- Waiting time reliability with randomly arriving passengers

  $$\text{Wait Time} = \frac{\text{Headway}}{2}$$

CHAPTER 4

Process for Prioritizing Operational and Capital Improvements

The project team agreed to model a future year of 2020 as doing so would require minimal network changes and, it was hoped, would allow for the model trip tables to work within the DTA without preconditioning. The project team also agreed to limit any network changes (automobile and transit) to the Southwest Corridor study area, because all the scenarios planned for simulation were within the TriMet service area. Metro staff worked closely with various stakeholder groups within Metro and the FAST-TrIPs team to identify the necessary transit changes that would need to occur to the base transit network for each of the scenarios. Here is the final list of scenarios:

1. **Bus rapid transit (BRT) to Tualatin, operating in an added exclusive transit right-of-way (ROW).** BRT would travel primarily on Barbur Boulevard between downtown Portland and the Tigard city line and through the Tigard Triangle to reach the downtown Tigard Transit Center. The alignment would use Hall Boulevard, Durham Road, and Upper Boones Ferry Road between Tigard and Tualatin, terminating at the Westside Express Service commuter rail station. This alternative would remove no roadway capacity.
2. **BRT to Tualatin, operating in converted automobile lanes, in an exclusive transit ROW.** Using the same alignment as the first alternative, this alternative would remove one lane of automobile capacity in each direction for the entire alignment where at least two automobile lanes currently exist for the exclusive use of transit vehicles. This BRT would be center running, restricting left-turn access for automobiles to signalized intersections.
3. **BRT to Tualatin, operating in converted automobile lanes, in business access and transit lanes.** This alternative would convert automobile lanes in the same road segments as the second alternative, but it would include a curbside-running BRT that would allow autos in the transit lane with restrictions. Automobiles would be allowed in the lane only to make right turns to exit the street to driveways or intersecting streets or to enter the street in order to merge into the general traffic lane.
4. **I-5 active traffic management.** This alternative would include installation of sensors and variable message signs, and use of other techniques such as variable speed limits, to reduce congestion and improve safety on I-5 for the length of the corridor.

Table 4.1 and Table 4.2 list additional proposed projects on I-5 and OR-99W, respectively, that were removed from consideration as part of the Southwest Corridor Plan.

The project team believes that these scenarios will provide a good mix of changes to both automobile and transit travel time reliability; they also provided our workshop participants with interesting data on the various trade-offs between automobile and transit projects. Once the BRT system is coded for one scenario, it should not require too much additional work to make it work in the other scenarios. Not all projects listed in Tables 4.1 and 4.2 were modeled. However, the project team did model simplified intelligent transportation systems–strategy scenarios by using variable message signs (VMSs) on Barbur and I-5. Details of such models are presented in Chapter 7.

Table 4.1. Scenario Details for I-5 Projects

Location	Project Details	Cost
I-5 Active traffic management	Install sensors and variable message signs and use other techniques, such as variable speeds, to reduce congestion and improve safety.	$7,000,000
I-5 Southbound climbing lane: Hood Avenue to Terwilliger Boulevard	Phase 1: Hood Avenue entrance–south of Corbett, $25M; Phase 2: south of Corbett-Brier Place, $18M; Phase 3: Brier Place-Terwilliger exit, $20M.	$250,000,000
I-5 Congestion and bottleneck operational improvements	This project would construct several improvements to address recurring bottlenecks on I-5 south of the central city. Two priority projects include constructing a southbound auxiliary lane along I-5 from the SW Lower Boones Ferry Road interchange to the SW Nyberg Street interchange and reconstructing the SW Lower Boones Ferry Road off-ramp from one to two lanes. Other projects include auxiliary lanes, ramp reconfigurations, changes to striping, and intelligent transportation systems. Could be constructed in phases.	$220,000,000
SW Portland I-5 diamond interchange	Construct a diamond interchange at I-5 and SW 26th, remove existing Spring Garden ramps, and remove northbound Taylor's Ferry off-ramp.	$86,000,000
SW Portland I-5 partial split interchange	Reconfigure the I-5 Spring Garden interchange as a partial split by creating I-5 southbound ramps connecting to Barbur Boulevard just south of SW 26th and creating northbound on- and off-ramps at Spring Garden. Would close existing southbound off-ramp at Spring Garden and northbound off-ramp at Taylor's Ferry. Could be constructed in two phases.	$79,900,000

Table 4.2. Scenario Details for OR-99W Projects

Location	Project Details	Cost
Highway 99W improvements (Cipole to Tualatin River)	Widen 99W to six lanes from Cipole to the Tualatin River.	$27,300,000
Highway 99W Transportation System Management and Operations	New Transportation System Management and Operations projects on OR-99W to install variable message signs, cameras, and road weather information systems.	$150,000
Highway 99W/68th Avenue	Intersection improvements such as protected left-turns at 68th (final improvements to be determined on further refinement).	$1,000,000
Highway 99W/I-5 southbound	Intersection improvements such as dual northbound through lanes on 99W and dual lanes for I-5 to reduce confusion, congestion, and related accidents (final improvements to be determined on further refinement).	$5,000,000
99W and Canterbury	Intersection improvements such as a westbound left-turn lane (final improvements to be determined on further refinement) at 99W and Canterbury.	$2,000,000
Highway 99W intersection improvements	Provide increased capacity at priority intersections, including bus queue bypass lanes in some locations, improved sidewalks, priority pedestrian crossings, and an access management plan, while retaining existing four- and five-lane facility from I-5 to Durham Road. Could be constructed in phases.	$94,900,000
Pacific Highway 99W (access management)	Implement access management strategies and median projects in Highway 99W Plan.	$6,000,000

CHAPTER 5

Analysis Model Preparation

5.1 Metro DynusT Dynamic Traffic Assignment Model Establishment and Calibration

For this project, Metro staff created a DynusT regional DTA model. Significant effort went into converting, coding, and debugging the regional model. Several challenging tasks, including setting up the signal timing and intersection turn bays, were carefully carried out by the Metro staff and supporting University of Arizona staff. Once the base model was set up, calibration was performed to ensure that the established DynusT model was consistent with the existing TDM from which prior scenario analysis results were produced. After several rounds of traffic flow model calibration, the final model parameters were chosen for freeways:

- Alpha = 2.3
- Jam density = 190
- Minimum speed = 5 mph

In addition, the freeway bias was set to 10%, and the entire regional model was run with all signals set to actuated (45-second maximum, 10-second minimum, 4-second amber) signals.

The DynusT model was validated against INRIX and count data. All the calibration efforts resulted in improved overall travel times and volumes when compared against INRIX and count data. When plotted against the static assignment results from the existing TDM based on Emme, the PM two-hour volumes from DynusT in the Southwest Corridor were still low on the major arterial (Barbur Boulevard), with differences averaging 42% lower in DynusT than in Emme (Figure 5.1). There was a much better fit on the freeways, with an average difference of 4% and $R^2 = 0.9407$.

Based on these results, the signals were changed to known timings (pretimed) along Barbur Boulevard and the on- and off-ramps for I-5 in the Southwest Corridor to see if a closer fit could be achieved between the models. These changes resulted in much better fit in the study area, with arterials averaging just 12% difference and freeways still averaging 4% difference. The overall R^2 was further improved to 0.9462 (Figure 5.2).

Next, travel times were compared between the Emme model and the DynusT model. Table 5.1 shows AM peak-period two-hour and midday one-hour travel time comparisons between the static model and DynusT. The statistics are categorized into three groups: all zones, either origin (O) or destination (D) in the Southwest Corridor, and both O and D in the Southwest Corridor.

Examined from the standpoint of percentage difference (% Difference in Table 5.1) for all three groups, midday travel times looked satisfactory, with zonal travel time differences ranging from only 7.5% to −11.1%. However, the difference increased for the peak-period results. When comparing all zone pairs in the region (4,600,000+), there was still a significant difference (~32%) between the DynusT and Emme model travel times. Much of this difference can be attributed to the actuated signals, which reach a maximum at 45 seconds in DynusT. On many corridors in the region, however, the maximum green time can exceed 100 seconds, and the edits to Barbur Boulevard in the model showed that changes in maximum green time can make a big difference in route selection and zone-to-zone travel time. So, either the maximum green time allowed for select actuated signals should be increased, or pretimed signal plans along select corridors should be manually input to get more reasonable regional DynusT travel times.

When comparing all O-D pairs either beginning or ending within the Southwest Corridor (1,000,000+), there was an even bigger discrepancy between weighted travel times (~37%). However, when focusing on those zone pairs contained wholly within the Southwest Corridor study area (66,500+), there was a much better fit between the models (~20% difference, representing less than 2 min).

Figure 5.3 shows the entire Portland regional highway network. The Southwest Corridor study area, shown in Figure 5.4,

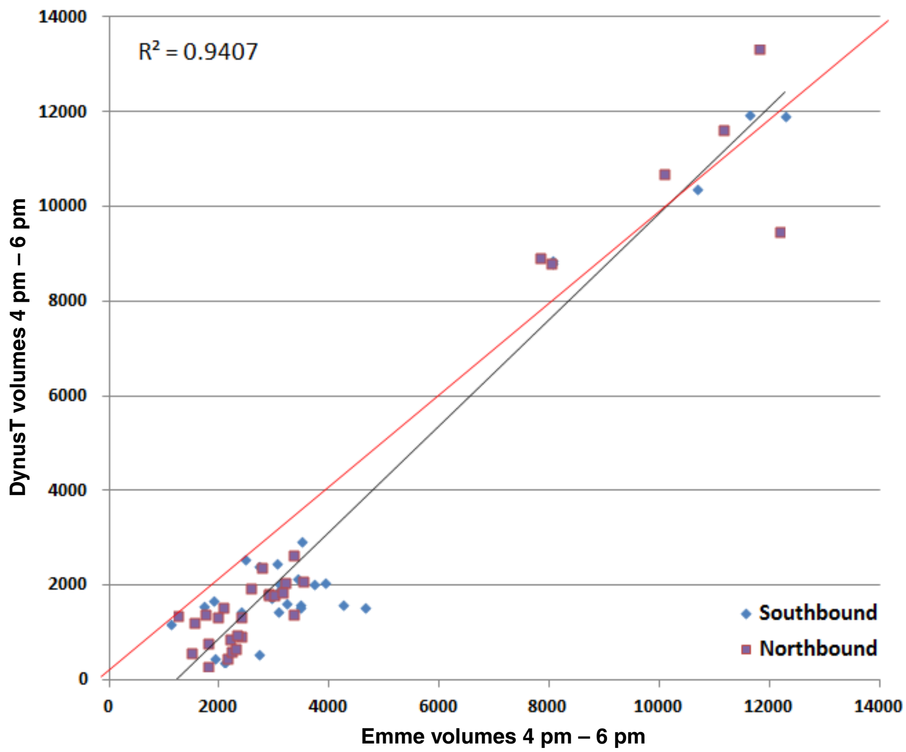


Figure 5.1. Comparison of 4 p.m. to 6 p.m. volumes between DynusT and Emme.

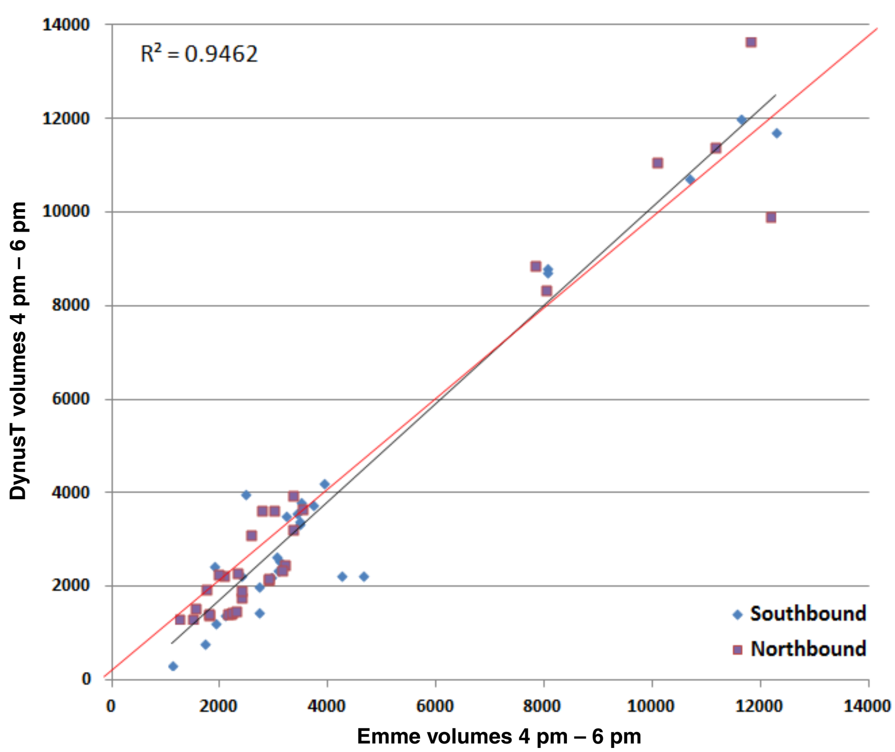


Figure 5.2. Improved 4 p.m. to 6 p.m. volume comparison between DynusT and Emme.

Table 5.1. AM Peak-Period Travel Time Comparison Between DynusT and Emme

Zone	No. of Zone Pairs	Weighted Mean AM 2-hour SOV Travel Time				Weighted Mean Midday 1-hour SOV Travel Time			
		Emme (min)	DynusT (min)	Difference (Emme – DynusT)	% Difference (from Emme)	Emme (min)	DynusT (min)	Difference (Emme – DynusT)	% Difference (from Emme)
All zones	4,674,244	15.54	20.56	–5.02	–32.3%	13.18	14.64	–1.46	–11.1%
O *or* D in SW Corridor	1,049,028	17.03	23.40	–6.37	–37.4%	13.96	14.87	–0.91	–6.5%
O *and* D in SW Corridor	66,564	8.55	10.28	–1.73	–20.2%	7.20	6.66	0.54	7.5%

Note: SOV = single-occupant vehicle.

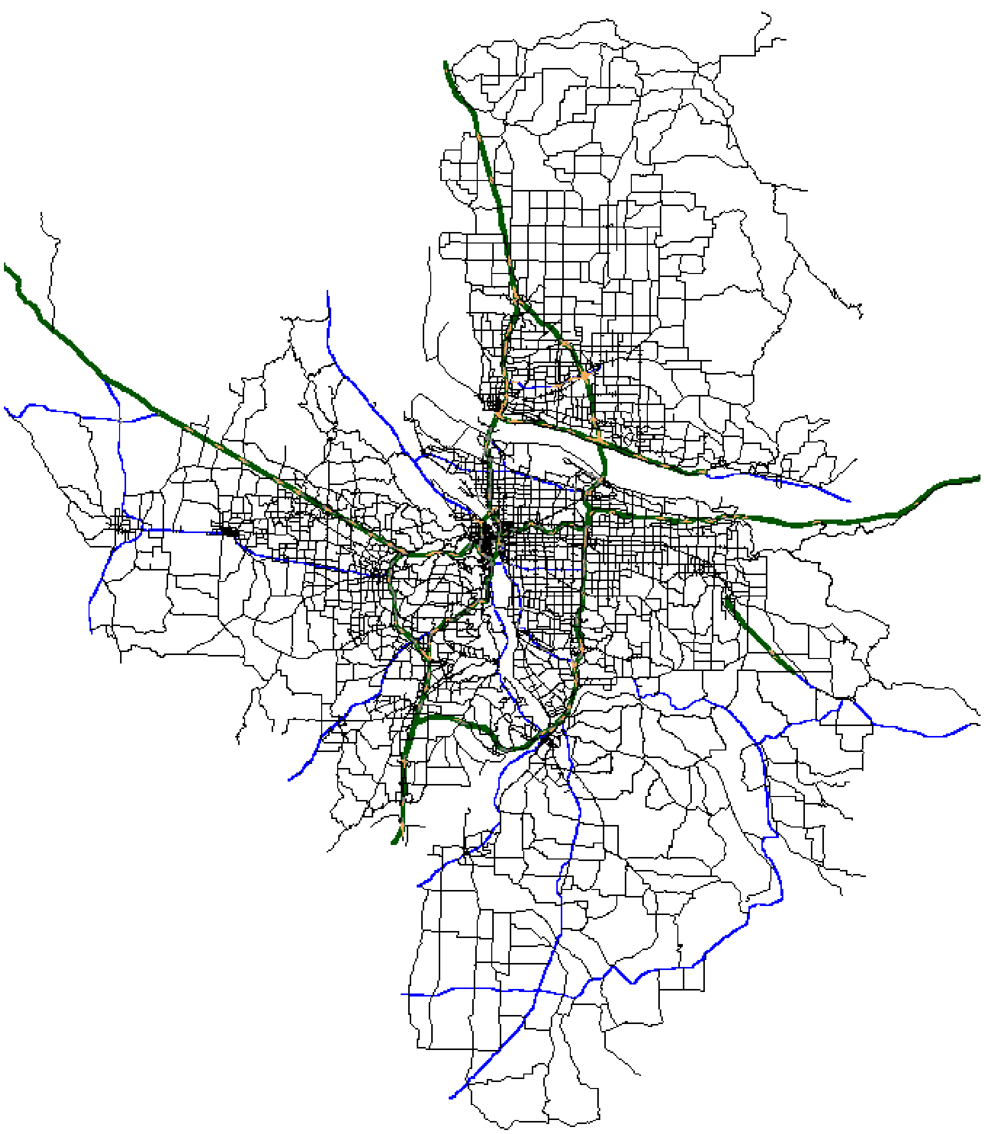


Figure 5.3. Portland regional highway network.

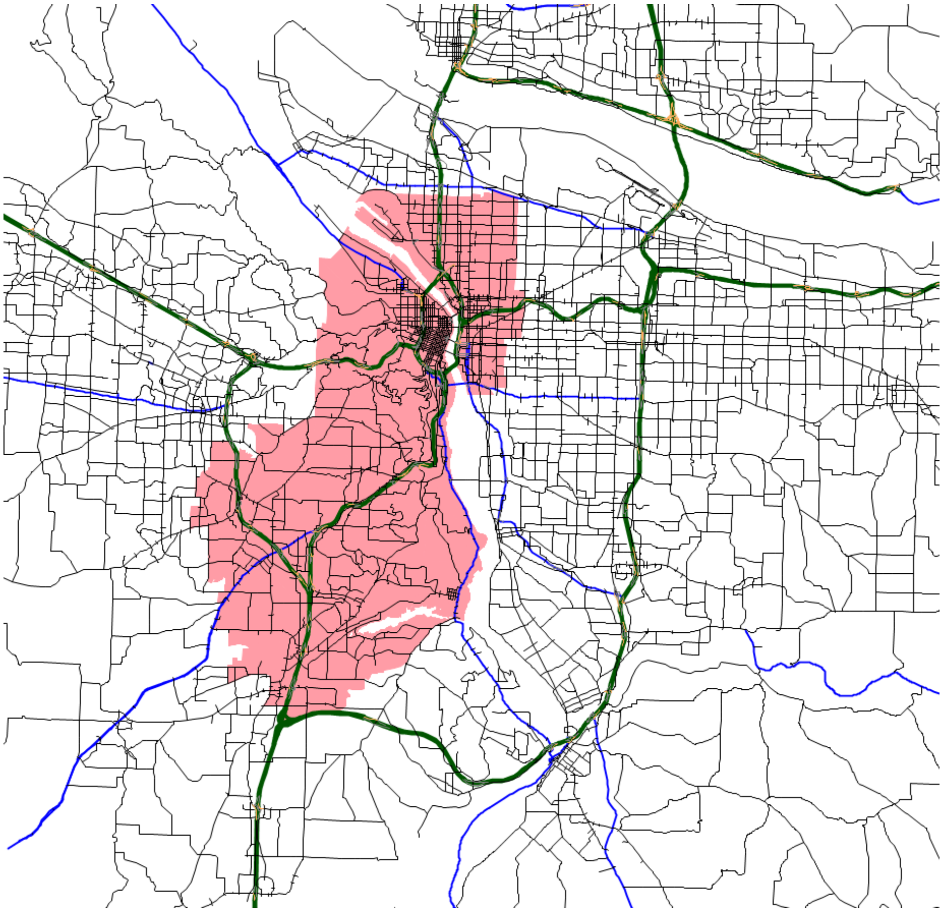


Figure 5.4. Southwest Corridor study area shown in coral.

encompasses 258 traffic analysis zones; this area actually contains most of the high-employment and residential areas that were of concern for the purposes of this study. This area includes the Portland central business district (CBD), the Lloyd District, Washington Square, Lake Oswego, Tualatin, Tigard, and much of the industrial northwest area of Portland.

The team decided to focus solely on DynusT and FAST-TrIPs travel times and reliability travel time equivalents (TTEs) only for those zone pairs contained within the study area and substitute Emme automobile and transit travel times for all other areas in the region. Using these times greatly improved the model calibration and allowed the team to move forward with TDM integration. The next step was the integration of DynusT and FAST-TrIPs and final integration of the dynamic models with the Metro TDM.

5.2 FAST-TrIPs Model Preparation and Coding

5.2.1 FAST-TrIPs Model Updates

As part of this project, the L35A team continued to make substantial improvements to the FAST-TrIPs model. The path search model (i.e., trip-based shortest path) in FAST-TrIPs was improved to be multithreaded, with significant speed-ups. In a test on a four-core machine, the run time was improved by up to 70%. A new submodel was added for passenger appearance at boarding stops. The submodel determines, based on the route headway, how early passengers show up at the stop.

Two new parameters in the route choice model can be used as a part of the path utility:

1. Transfer penalty, to add inconvenience cost to each transfer, in addition to the transfer wait/walk time.
2. Fare, to incorporate the cost of boarding a transit vehicle. The value of travel time is generic at this time, but it can be individualized as needed.

A skim-generation module was added, and the passenger waiting function was updated. Additional Southwest Corridor skim-generation code was updated in terms of Metro TDM–FAST-TrIPs integration.

5.2.2 General Transit Feed Specification Network Updates

To aid DynusT and FAST-TrIPs integration, General Transit Feed Specification (GTFS) IDs were updated. C-TRAN (Clark

Table 5.2. Transit Network

Operators[a]	TriMet, C-TRAN, SMART
Routes	124
Trips	7,670
Stops	8,525
Stop times	417,007

[a] Sandy Area Metro and Canby Area Transit are not included because no general transit feed specification files were provided.

County, Washington) and SMART (Southern Metro Area Regional Transit) transit network and schedule times (GTFS) were added on the existing network (TriMet). The L35A team researched various methods to streamline this process with the aim of helping future model users reduce the time needed to prepare the transit route information for use in the modeling environment. Table 5.2 shows the transit network.

Similarly, the team also checked the basic differences between FAST-TrIPs and the Emme model; all-to-all and Southwest Corridor area transit skims were compared. Transit assignment coverage by the skims from FAST-TrIPs was analyzed by comparing it with the coverage of the existing Emme model, and to increase accessibility, additional access links were added to the existing data set to improve the accessibility for transit passengers.

5.2.3 Transit Scenario Preparation

The coding for transit scenarios started from coding all routes, stop locations, and the schedule of every bus trip. New light rail transit and BRT services for the Southwest Corridor were prepared, and additional route changes on the existing routes were considered. More specifically, GTFS files were prepared for new light rail transit and BRT services, the existing three transit routes (12, 76, and 94), and the new Route 93.

Developing the bus transit network for DynusT simulation was a major undertaking for a multimodal traffic simulation. GTFS files were imported into DynuStudio for editing and precise mapping of transit routes link by link onto the automobile network. A diagram of bus routes is shown in Figure 5.5. The script for generating transitrouteschedule.dat was also developed by the team, and the interface to the DynuStudio transit module was implemented.

Buses were included in the DynusT mixed-mode DTA simulation, and transit times were produced as main outputs to be fed into FAST-TrIPs. Nearly 3,200 buses were included in the transit demand for the entire simulation period. Figure 5.6 and Figure 5.7 display assigned bus volumes on the highway network and at stops, respectively.

5.3 DynusT and FAST-TrIPs Integration

The DynusT–FAST-TrIPs integration process involves the following steps:

1. FAST-TrIPs is run with the real demand from 11 a.m. to 7 p.m. This run will produce an output file named ft_output_loadProfile.dat that contains information about transit dwell time.

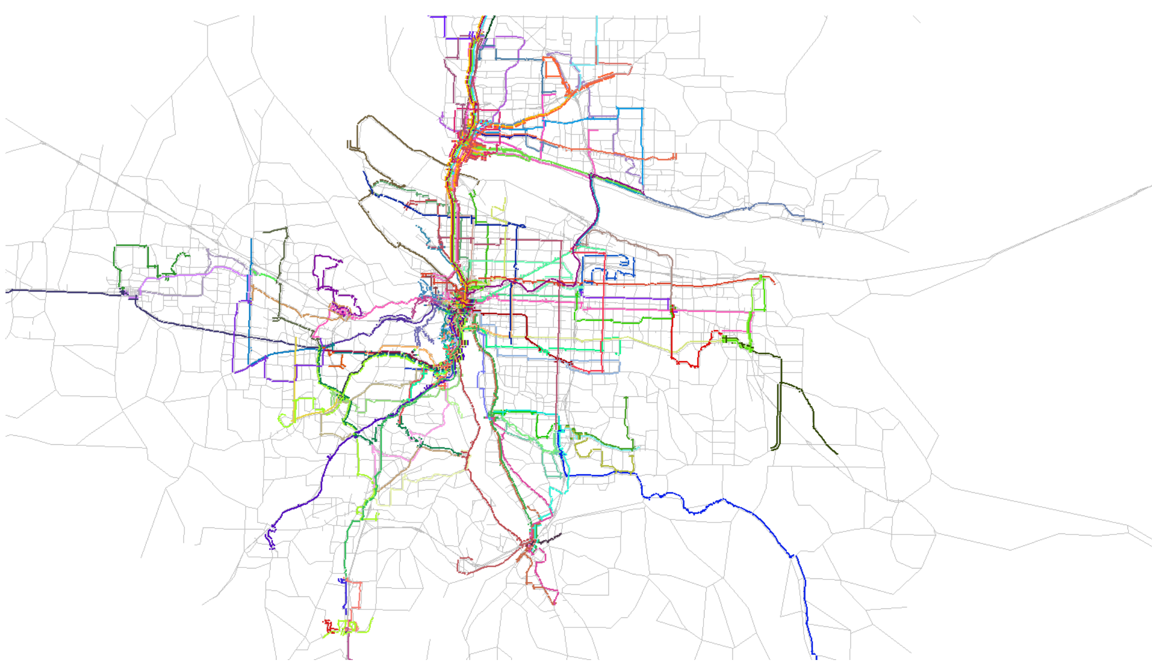


Figure 5.5. Bus routes shown in each color-coded line.

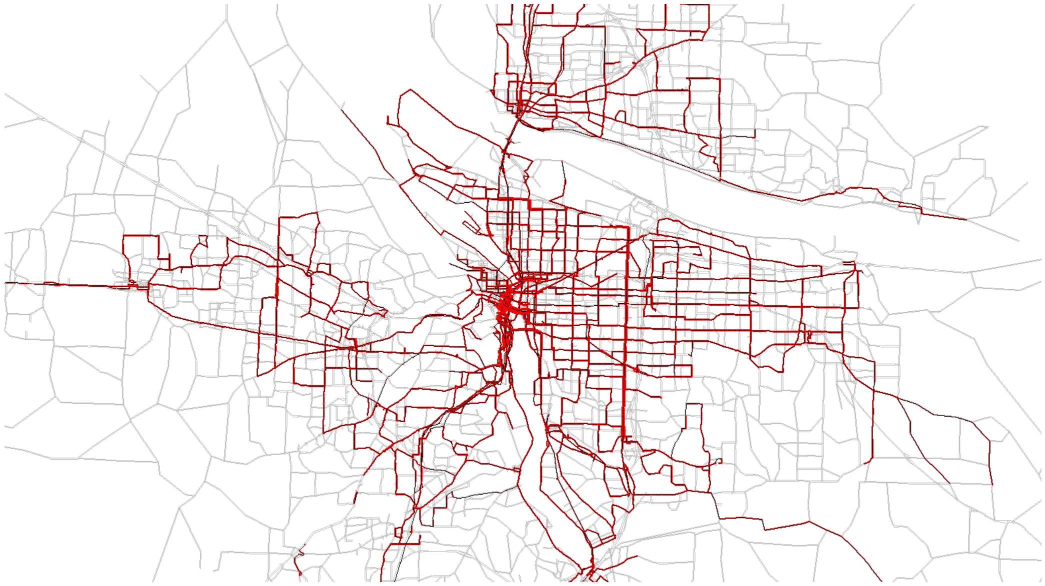


Figure 5.6. Bus volumes on highway network shown in red bandwidth plot.

2. The transit dwell information produced by FAST-TrIPs can be used for the DynusT run in order to account for the delay at transit stops. However, ft_output_loadProfile.dat cannot be directly used by DynusT. A Python script is needed to convert ft_output_loadProfile.dat to TransitDwellTime.dat.
3. Next, DynusT is run for the whole period (11 a.m. to 7 p.m.) to generate the automobile skims.
4. Running DynusT for the whole period will generate an output file named AltTime_Transit.dat that contains all the transit stop time information. However, as in Step 2, this file cannot be directly used by FAST-TrIPs, and a Python script is applied to convert the contents of this file to an input file for FAST-TrIPs called ft_input_StopTimes.dat.
5. Using the stop time information, FAST-TrIPs can then be run to produce all-to-all transit skims by applying a fake all-to-all demand for auto. At this point, the FAST-TrIPs parameters setting should be changed such that instead of using the schedule, FAST-TrIPs uses vehicle trajectories. Because FAST-TrIPs runs cannot be conducted simultaneously, two FAST-TrIPs runs should be conducted

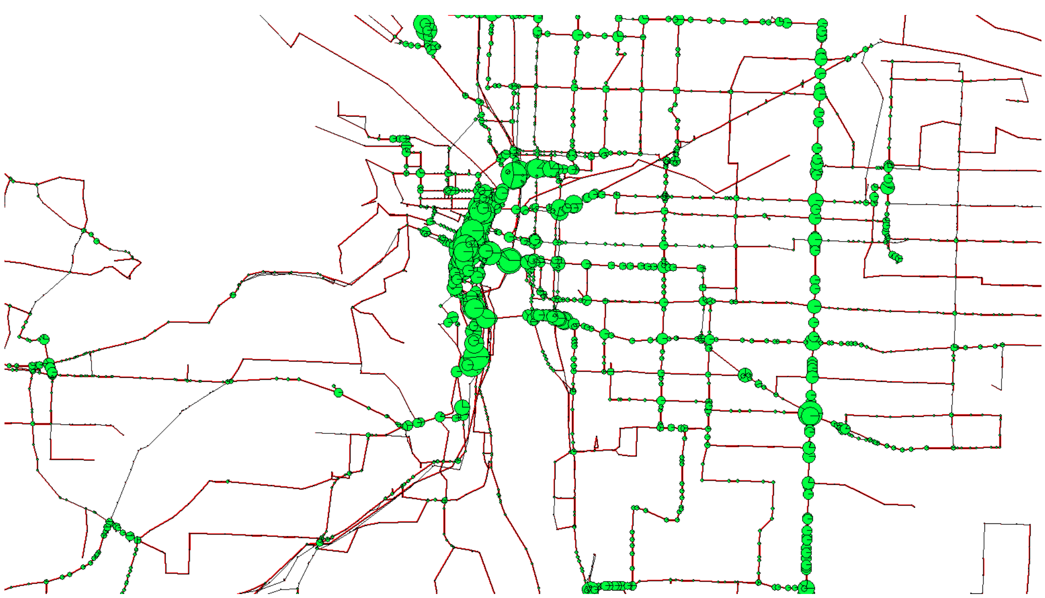


Figure 5.7. Bus volumes at stops shown by different-sized green circles.

separately using the corresponding fake automobile demand to produce the midday (12 to 1 p.m.) and peak afternoon (4 to 6 p.m.) sets of transit skims.

6. Once the automobile and transit travel time skims are generated, they will be incorporated into the regional TDM to produce the final trip tables. TDM forecasts destinations and mode choices and produces hourly trip tables for final assignment. To conclude the process, the integrated DynusT–FAST-TrIPs model should be run once again using final hourly trip tables produced by the TDM.

These steps are summarized in the flowchart shown in Figure 5.8.

The integration of DynusT and FAST-TrIPs was conducted under the DynuStudio platform. The complete integration method is explained in Appendix B.

5.4 Base Model Evaluation

Both the DynusT and FAST-TrIPs skims were incorporated into the Metro regional TDM. The skims were verified as reasonable by Metro staff. Reasonable destination and mode choice results were anticipated from both the DynusT and FAST-TrIPs skims. The histograms in Figures 5.9 through 5.12 show travel time differences between Emme static results and DynusT–FAST-TrIPs dynamic results for zone pairs within the subarea.

Given the complexities associated with the FAST-TrIPs networks, these differences are reasonable, especially because travel time reliability is incorporated into the route choice for DynusT–FAST-TrIPs but not in the static assignments. Figures 5.9 and 5.10, respectively, are for AM peak and midday automobile travel. Figures 5.11 and 5.12 are for the same periods for transit travel.

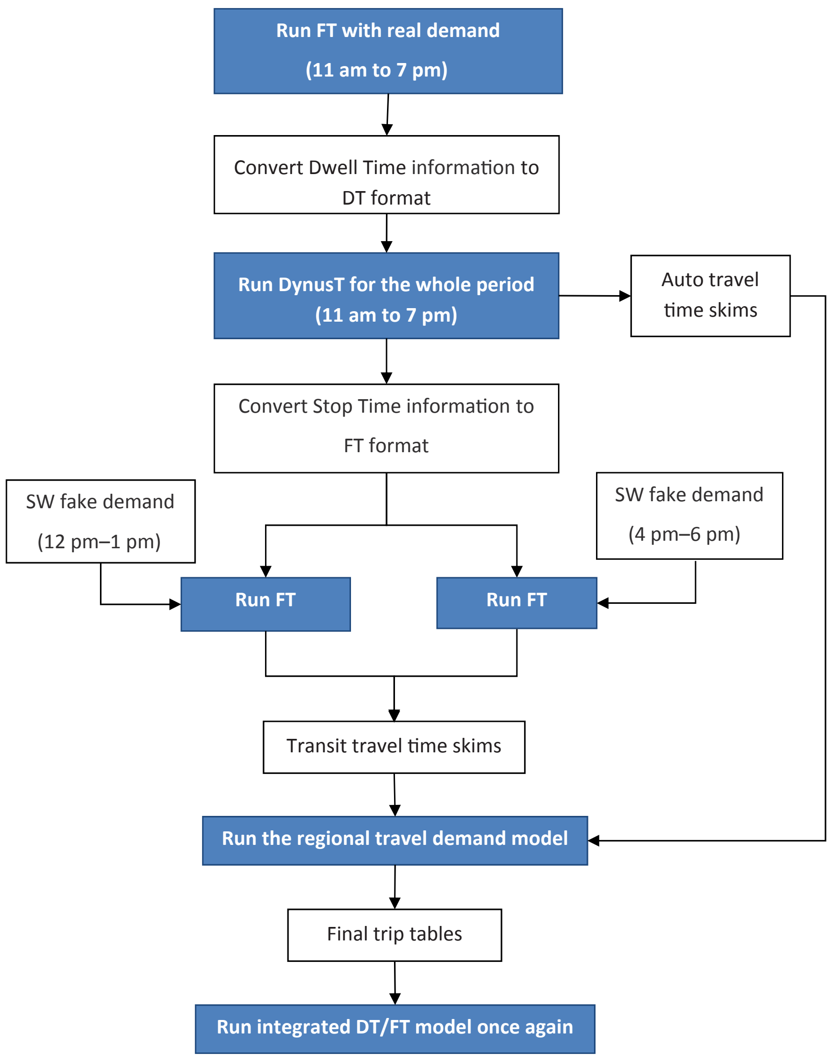


Figure 5.8. The DynusT–FAST-TrIPs integration framework.

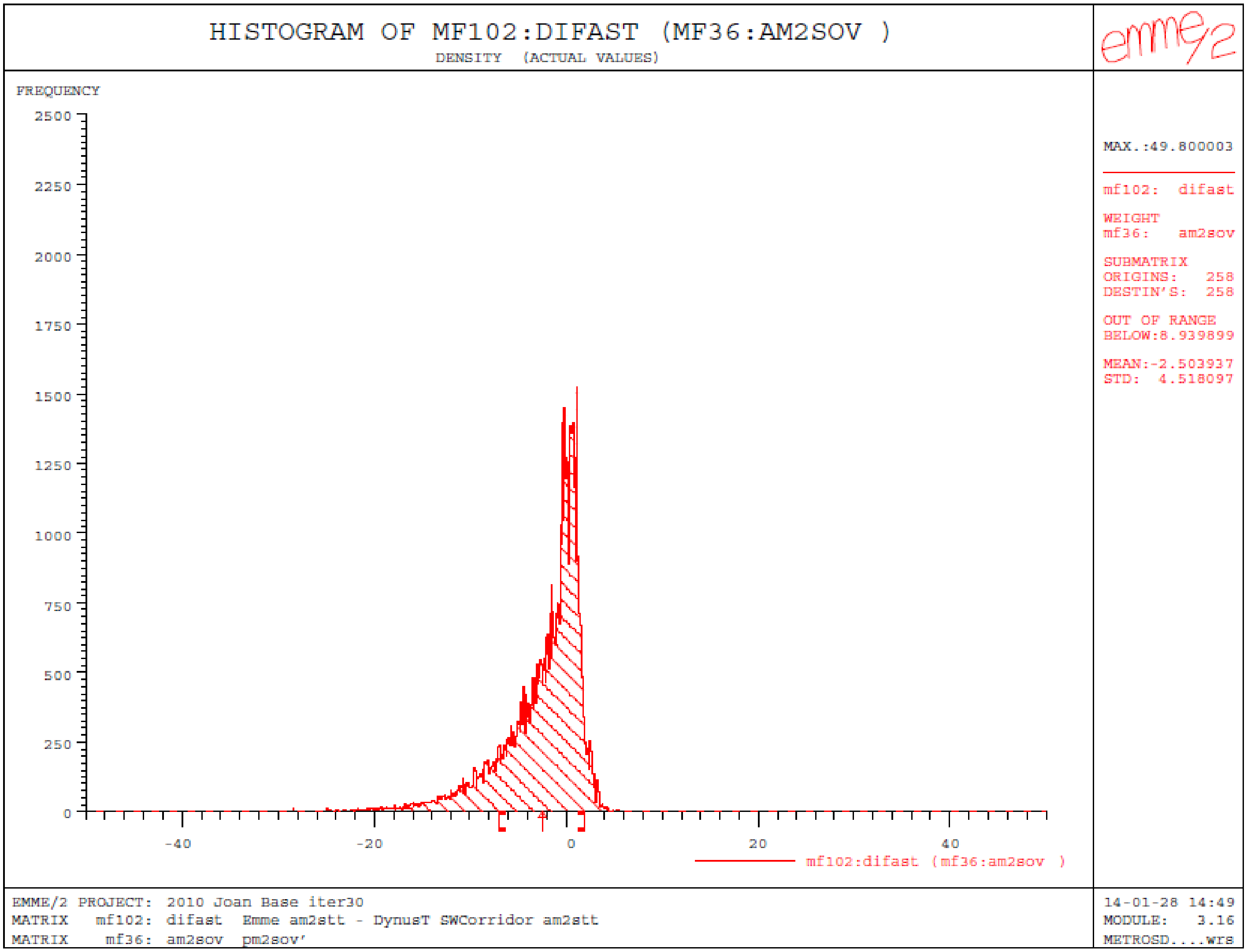


Figure 5.9. Difference in AM peak-period SOV automobile travel times for Southwest Corridor zone pairs (weighted by trips): mean = —2.5 min, standard deviation = 4.5 min.

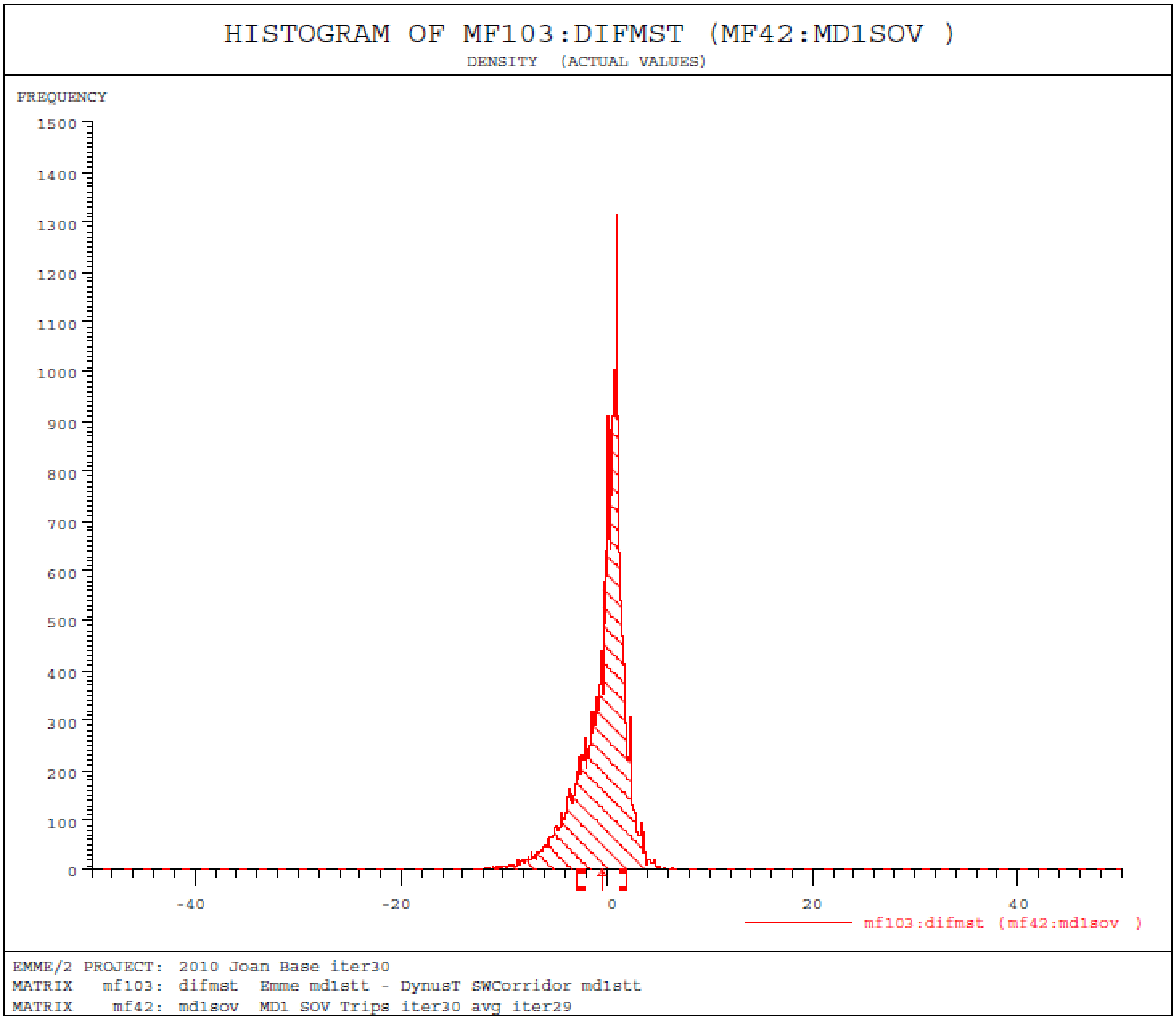


Figure 5.10. Difference in midday SOV automobile travel times for Southwest Corridor zone pairs (weighted by trips): mean = −0.4 min, standard deviation = 2.4 min.

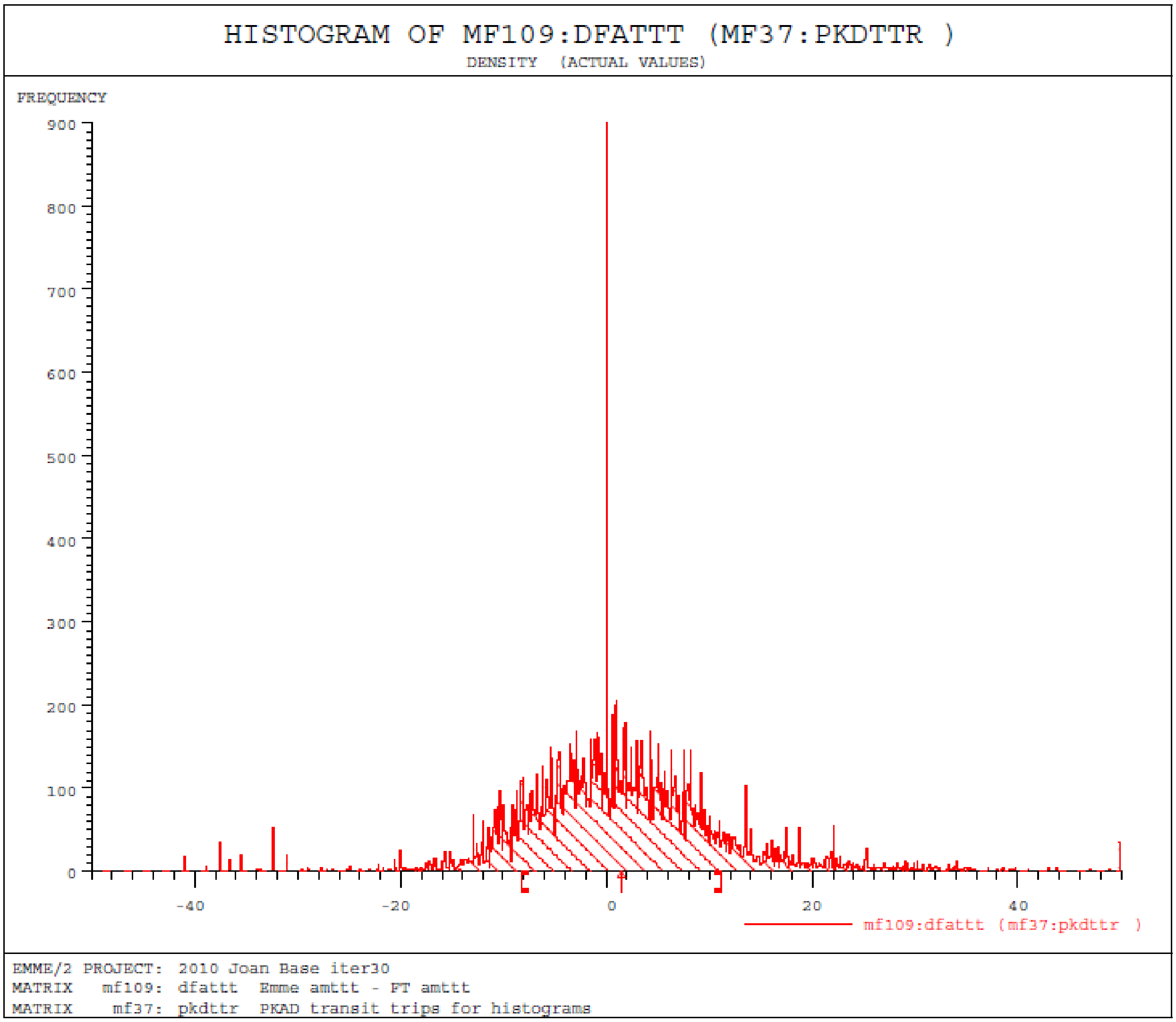


Figure 5.11. Difference in AM peak-period total transit travel times for Southwest Corridor zone pairs (weighted by trips): mean = 1.4 min, standard deviation = 9.7 min.

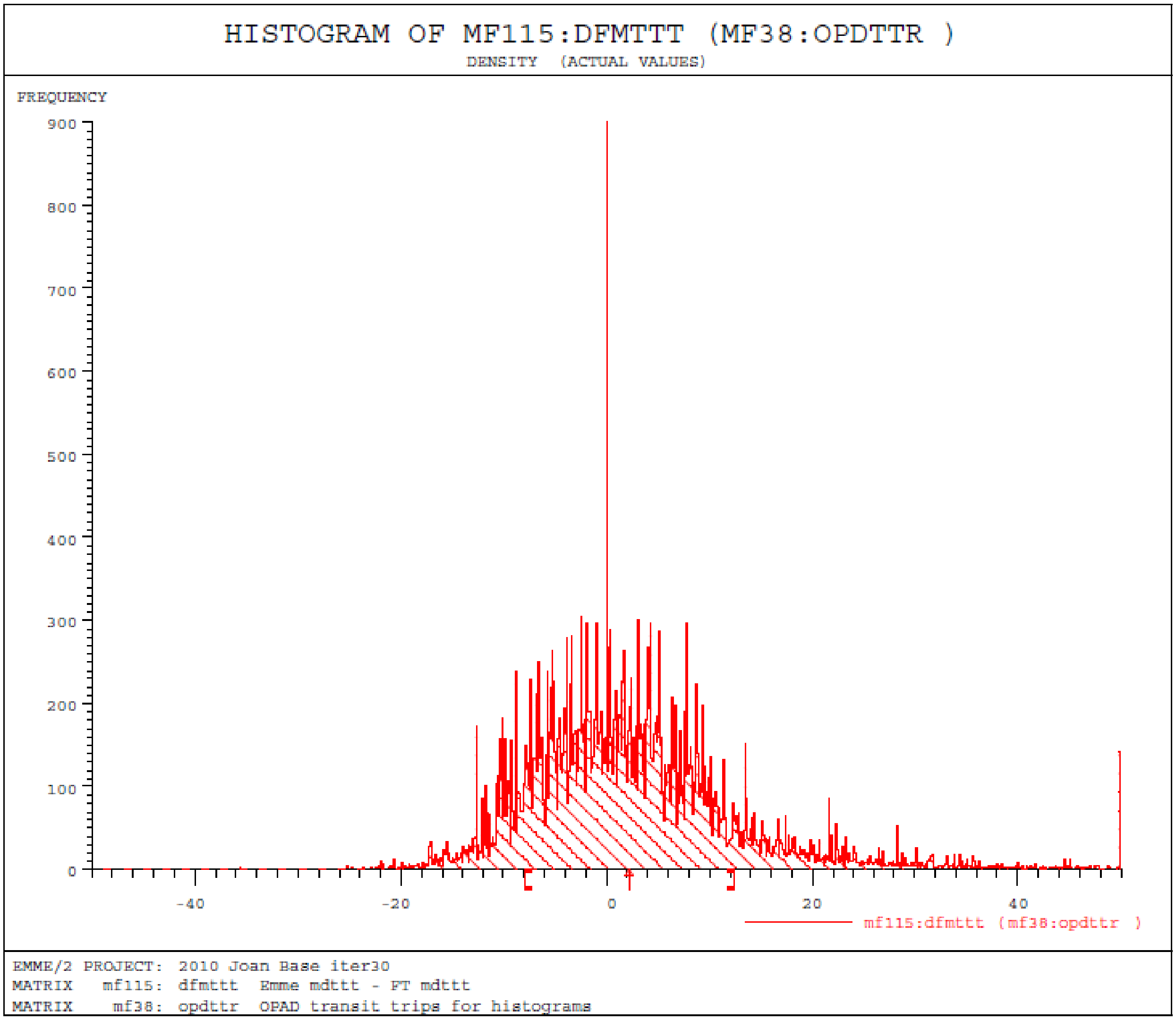


Figure 5.12. Difference in midday total transit travel times for Southwest Corridor zone pairs (weighted by trips): mean = 2.2 min, standard deviation = 10 min.

CHAPTER 6

Scenario Descriptions

6.1 Study Area

The Southwest Corridor Plan, which is illustrated in Appendix A, integrates multiple efforts: local land use plans to identify actions and investments that support livable communities; a corridor refinement plan to examine the function, mode, and general location of transportation improvements; and a transit alternatives analysis to define the best mode and alignment of high-capacity transit to serve the corridor. The plan is a partnership between Metro, Multnomah County, Washington County, the Oregon DOT, TriMet (the Portland region transit agency), and the cities of Portland, Sherwood, Tigard, Tualatin, Beaverton, Durham, King City, and Lake Oswego. The project uses a technical advisory committee, a project team leaders' group, and a steering committee made up of representatives of local jurisdictions to advise and contribute to the process. A project map of the Southwest Corridor Plan is shown in Figure 6.1.

6.2 Descriptions of Scenarios

Scenarios analyzed by this study are described as follows:

- **Scenario 1.** This scenario included only the base network without any BRT or intelligent transportation system strategy. No reliability measure was modeled; that is, DynusT and FAST-TrIPs assignments were based entirely on travel time without incorporating travel time reliability.
- **Scenario 2.** This scenario was similar to Scenario 1 except that reliability measures were included.
- **Scenario 3.** This scenario incorporated BRT into the base network on Barbur Boulevard operating in mixed traffic. This scenario was equivalent to a typical transit route, but with improved bus frequencies and fewer stop locations. These alterations represented a minimal improvement to the transit service within the corridor without any change in existing transit or auto right-of-way (ROW).
- **Scenario 4.** This scenario was similar to Scenario 3 but with BRT operating in a dedicated ROW by taking up one existing lane.
- **Scenario 5.** This scenario was similar to Scenario 3 but with BRT operating in a dedicated ROW by adding one lane.
- **Scenario 6.** This scenario was Scenario 3 with the addition of several variable message signs (VMSs) along Barbur and I-5.
- **Scenario 7.** This scenario was Scenario 4 with the addition of several VMSs along Barbur and I-5.
- **Scenario 8.** This scenario was Scenario 5 with the addition of several VMSs along Barbur and I-5.

Scenarios 9 through 15 were similar to Scenarios 2 through 8 with reliability measures not being considered. All scenarios are summarized in Table 6.1. Cross sections of the scenarios are shown in Figures 6.2 through 6.4 to better illustrate their differences. BRT line coding and the VMS locations along the Southwest Corridor are shown in Figures 6.5 and 6.6, respectively.

6.3 Scenario Coding

Scenarios 3, 4, and 5 included the following adjustments to the local bus network in coordination with BRT service:

- Route 12 frequency was reduced between Tigard and downtown Portland where BRT service operates.
- Route 76 was rerouted from SW Hall Boulevard to SW 72nd Avenue in Tigard to avoid duplicating BRT routing.
- Route 94 frequency was increased between Sherwood and Tigard.

In all the scenarios beyond the first two—which were essentially the base network—modeling the scenarios entailed coding the BRT plus "Other Buses" changes into the DynuStudio FAST-TrIPs base network. After running the new transit coding in FAST-TrIPs, the standard DynusT model was run to

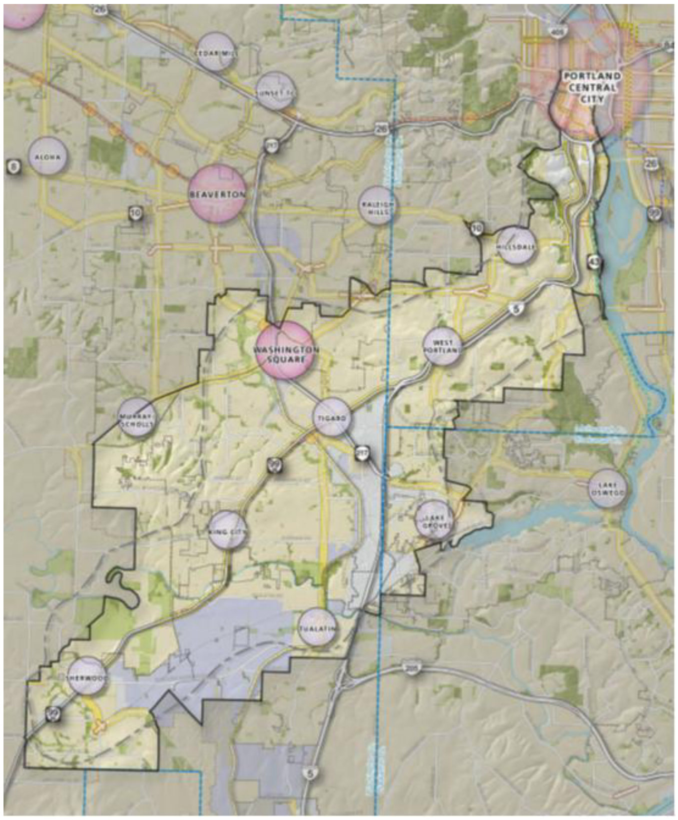


Figure 6.1. Southwest Corridor project map.

Table 6.1. Scenario Summary

Scenario	Reliability	Interaction with Other Traffic	Existing or New Lane	VMS
1	No	na	na	No
2	Yes	na	na	No
3	Yes	Mixed with Traffic	na	No
4	Yes	Dedicated Lane	Existing	No
5	Yes	Dedicated Lane	New	No
6	Yes	Mixed with Traffic	na	Yes
7	Yes	Dedicated Lane	Existing	Yes
8	Yes	Dedicated Lane	New	Yes
9	No	na	na	No
10	No	Mixed with Traffic	na	No
11	No	Dedicated Lane	Existing	No
12	No	Dedicated Lane	New	No
13	No	Mixed with Traffic	na	Yes
14	No	Dedicated Lane	Existing	Yes
15	No	Dedicated Lane	New	Yes

Note: na = not applicable.

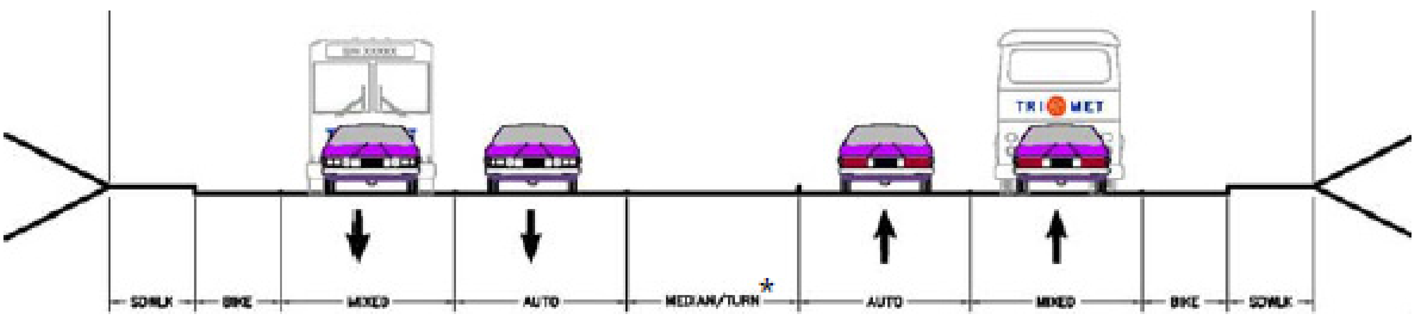


Figure 6.2. Cross sections of Scenarios 1, 2, 3, and 6.

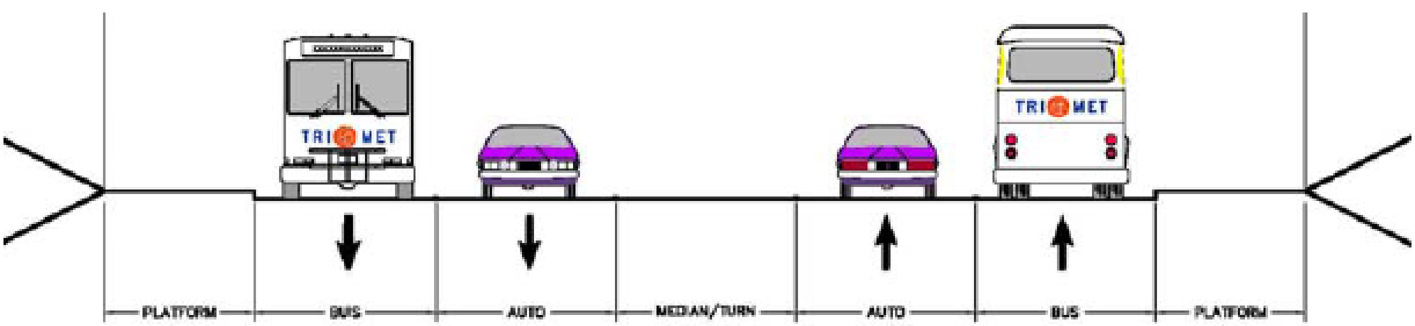


Figure 6.3. Cross sections of Scenarios 4 and 7.

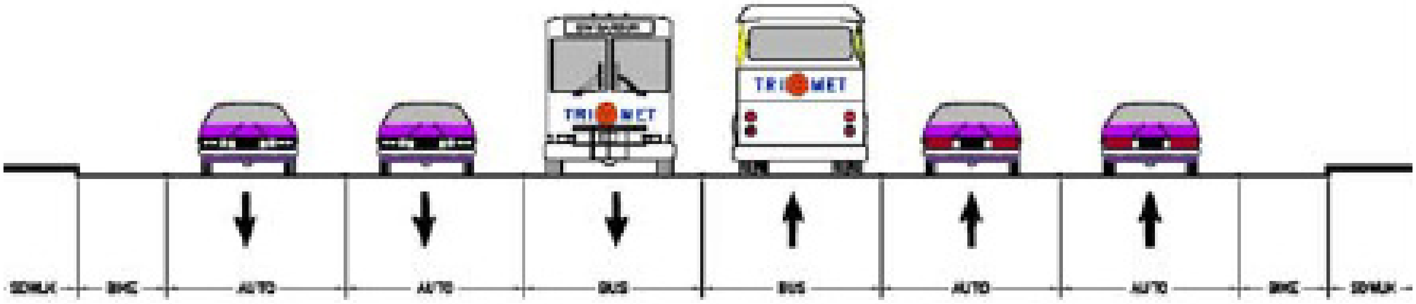


Figure 6.4. Cross sections of Scenarios 5 and 8.

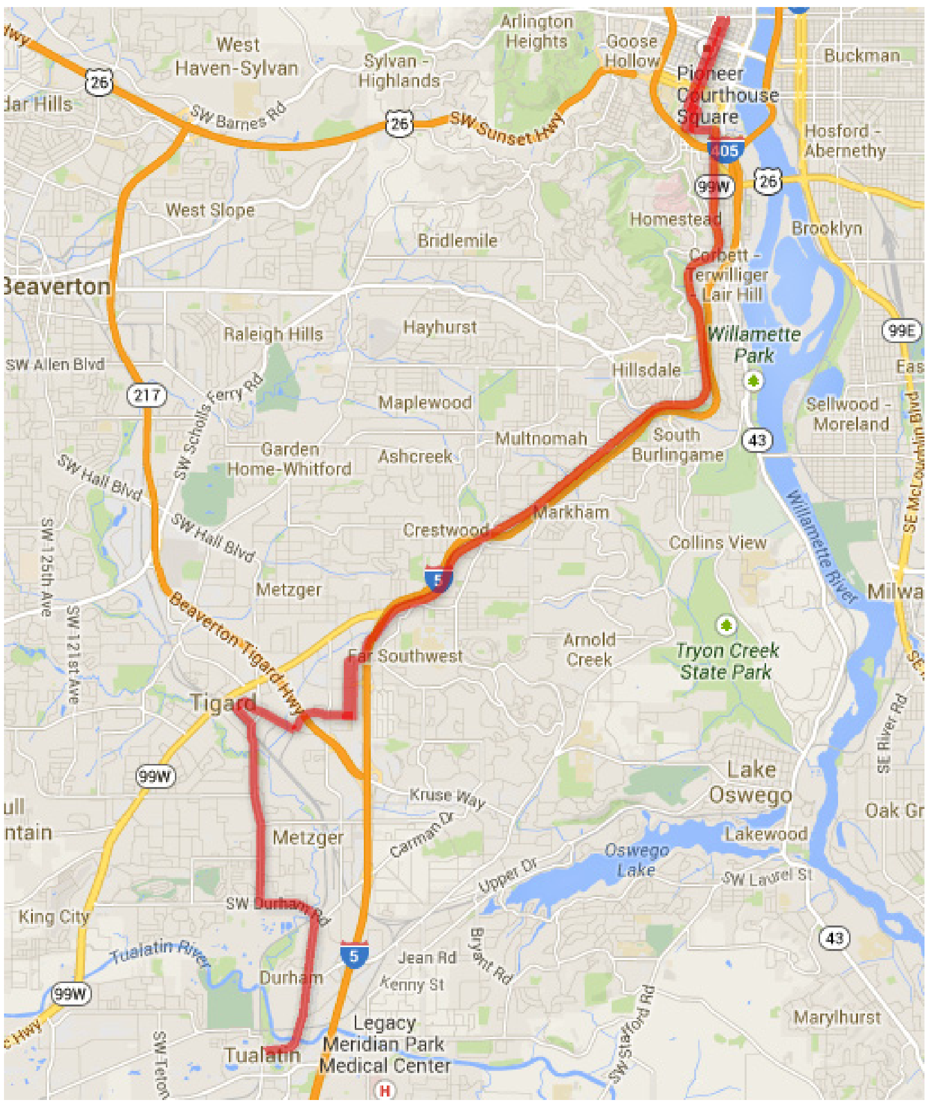


Figure 6.5. Southwest Corridor BRT line coding.

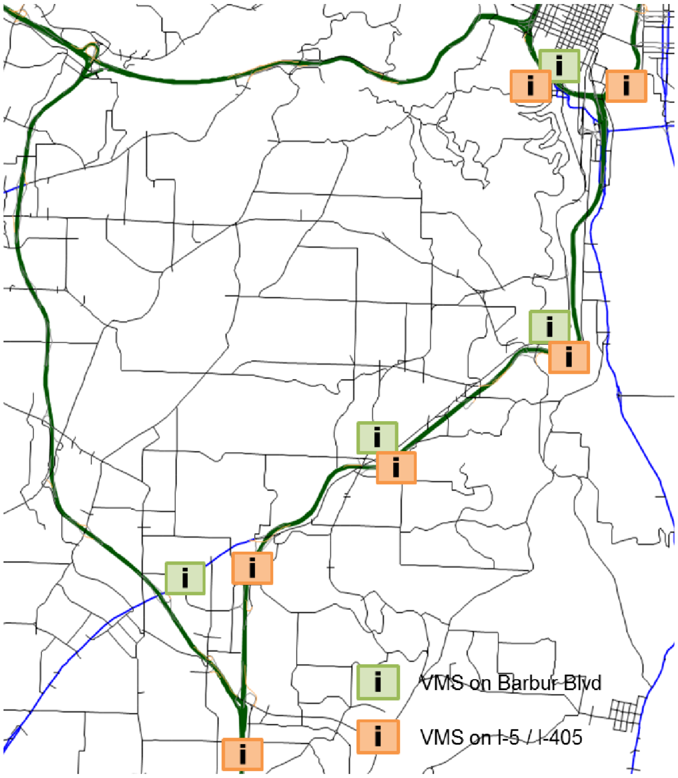


Figure 6.6. Variable message sign (VMS) locations.

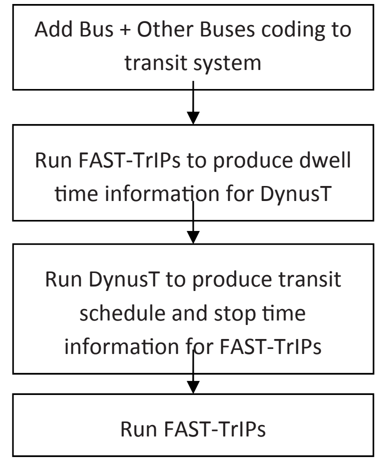


Figure 6.8. Scenario coding flowchart for Scenarios 3 and 6 (BRT in mixed traffic).

create the transit schedule, which was then fed into FAST-TrIPs. The process generally followed the steps shown in Figure 5.8. The flowcharts of Figures 6.7 and 6.8, respectively, show the coding process for Scenarios 1 and 2 and Scenarios 3 and 6.

For Scenarios 4 and 5 (and similarly for Scenarios 7 and 8), the process varied slightly, as these scenarios assumed that BRT runs on a separate ROW dedicated solely to high-capacity transit. In these scenarios, instead of coding ROW directly, DynusT was run twice. The first run was with very little demand to simulate the situation that buses were traveling in free-flow conditions, and the second run was with full demand to simulate buses traveling in full-demand conditions. After these two separate DynusT runs were completed, the two AltTime_Transit.dat files were used to produce the FAST-TrIPs transit schedule. The file from the full-demand DynusT run was used for coding transit for the entire system, and the BRT coding section was substituted from the results of the free-flow DynusT run. This coding reflects a bus running in a dedicated ROW and was fed into FAST-TrIPs. The coding for these scenarios is illustrated in Figure 6.9.

Although different services (e.g., bus, BRT, rail) may be run separately in DynusT, or if some routes are not simulated (e.g., rail) and so are separate, all the routes should be provided to FAST-TrIPs in a single file (ft_input_stopTimes.dat).

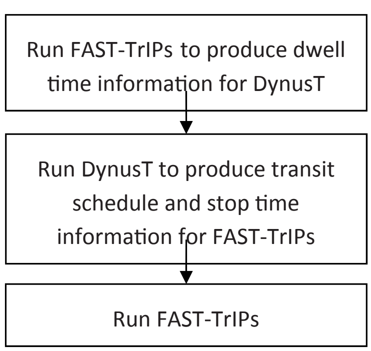


Figure 6.7. Scenario coding flowchart for Scenarios 1 and 2 (base network).

6.4 Model Feedback Framework

The feedback framework implemented for this project as shown in Figure 6.10 started from initial DynusT and FAST-TrIPs assignment to obtain skim (zone-to-zone travel time) information. The skim information was then returned to the mode choice model in the Metro TDM to estimate the mode shift due to the change of skim data that resulted from the initial assignment. The new estimated demand information for all the modes was then fed into DynusT–FAST-TrIPs again as the final assignment. The results reported here are from the final runs.

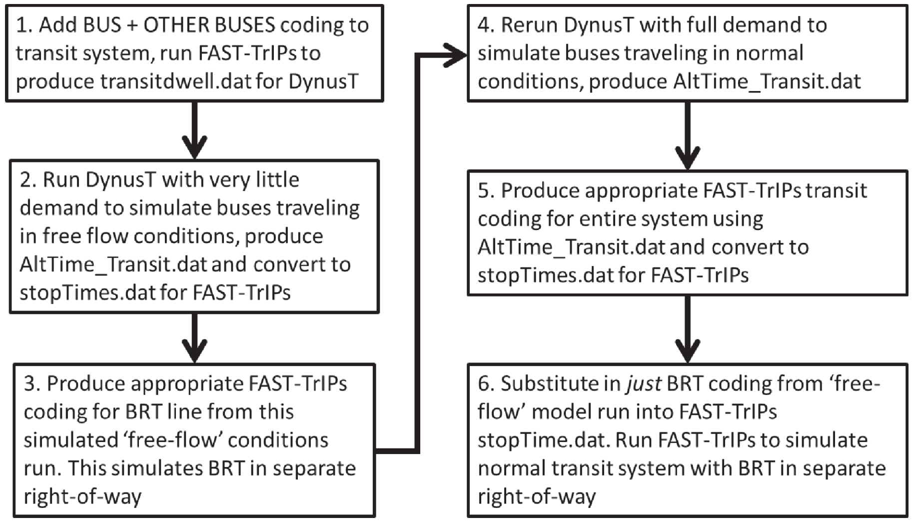


Figure 6.9. Scenario coding flowchart for Scenarios 4, 5, 7, and 8 (BRT in dedicated right-of-way).

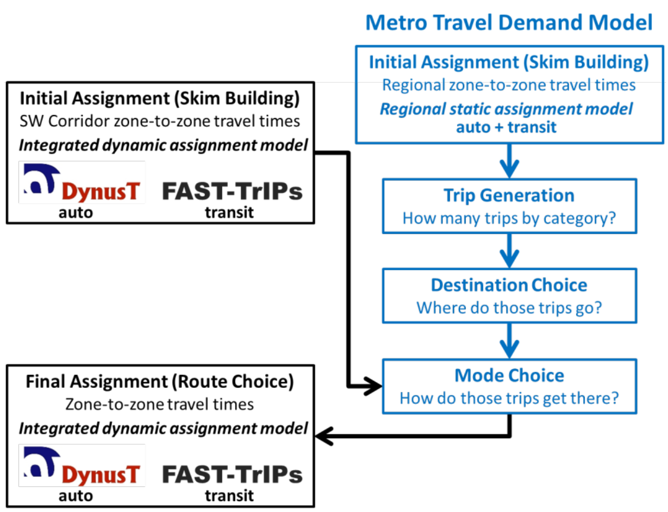


Figure 6.10. Feedback framework.

CHAPTER 7

Scenario Analysis

All the planned scenarios went through the complete modeling process depicted in Figure 6.10. A video showing the simulation of DynusT is available at http://youtube/FslkZE_ztAs.

7.1 Route Options

The route options displayed in Figure 7.1 illustrate route utilization under different reliability considerations. When reliability is not considered for a Tigard–Portland central business district (CBD) O-D pair, a longer and less reliable route (blue route in Figure 7.1a) is considered in the route set. When a reliability measure is considered, a set of shorter routes considered by users is shown. That set excludes the blue route.

A similar route set pattern is observed for the Tualatin–Portland CBD O-D pair (Figure 7.2). The case considering reliability measures includes fewer routes as it omits longer and less robust routes. Such assessments were confirmed by local commuters with actual experience with the corridor.

7.2 Impact of Reliability on Perceived Travel Times

7.2.1 Tigard and Portland CBD

Further details from skims prompted some insights regarding the composition of travel time equivalents (TTEs). For the same Tigard–Portland CBD O-D pair in the baseline with reliability case, the total TTE was 48 min and travel time was 41 min, indicating a 7 min TTE of reliability. In the case of BRT operating in an exclusive ROW via adding a new lane, with reliability the TTE was 46 min and travel time was 40 min, meaning a 6 min TTE of reliability. Despite a 1-min difference, both cases exhibit comparable TTEs of reliability. Figure 7.3 shows the peak-period TTEs for Tigard and the Portland CBD.

7.3 Impact of Reliability on Transit Mode Shares

Considering reliability generally leads to a slightly increased transit ridership share compared to a no-reliability case, as shown in Figure 7.4. Comparing three no-reliability scenarios (the baseline case, BRT in an exclusive ROW via an added lane, and VMS + BRT in an exclusive ROW via an added lane) revealed a generally increased ridership share for BRT (increase from 4.15% in the baseline case to 4.5% in the BRT in the exclusive ROW via an added lane case), but a slightly decreased ridership share for the VMS + BRT case compared to BRT.

The same scenarios analyzed by including a reliability measure revealed a similar trend across the three scenarios, but the reliability cases generally concluded with an approximately 1% increase in ridership compared to the no-reliability cases. This difference is due primarily to the fact that including a reliability measure increases the impedance of automobile traffic. However, such reliability-related impedance is minimal for BRT, because BRT travels on the dedicated ROW and hence is less likely to be affected by congestion on the automobile network. The ridership differences among scenarios were generally less than 1.0%. The differences were likely to be subject to the randomness of the mesoscopic simulation. Nonetheless, considering that the total share of transit in the study corridor is only about 4%, the range of differences appears to be intuitive.

7.4 Transit Mode Shares by Scenarios

The transit market shares under the four scenarios displayed in Figure 7.5 appear to be intuitive, with transit accounting for about a 4.33% mode share in the baseline case, 4.74% in the BRT in exclusive ROW via an added lane case, 4.88% in the BRT in exclusive ROW via a take a lane case, and 4.65% in

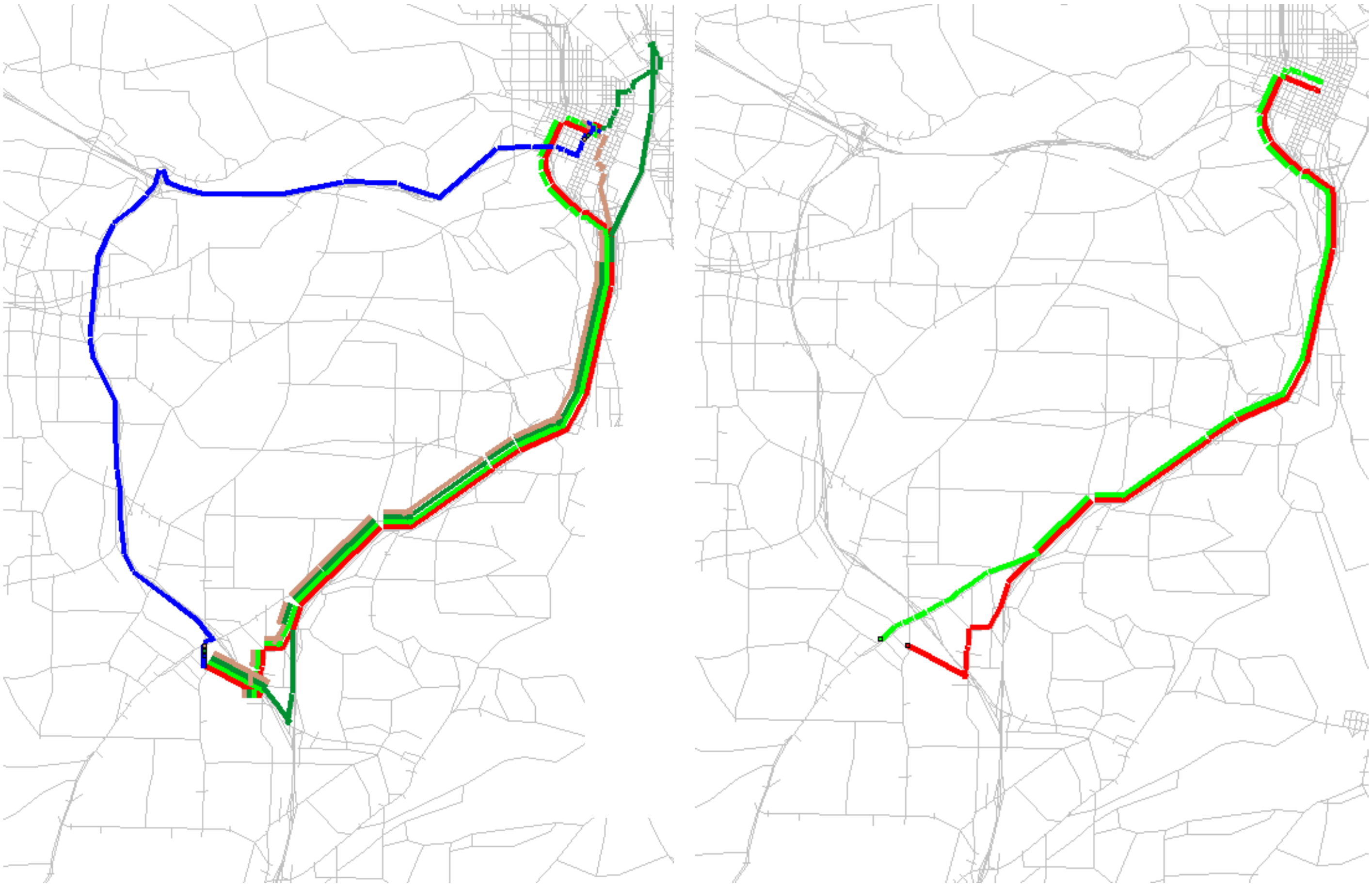


Figure 7.1. Route choice options between Portland central business district (CBD) and Tigard.

the BRT in mixed traffic case. One could understand these differences from the standpoint of traffic conditions for both automobile and BRT in each scenario.

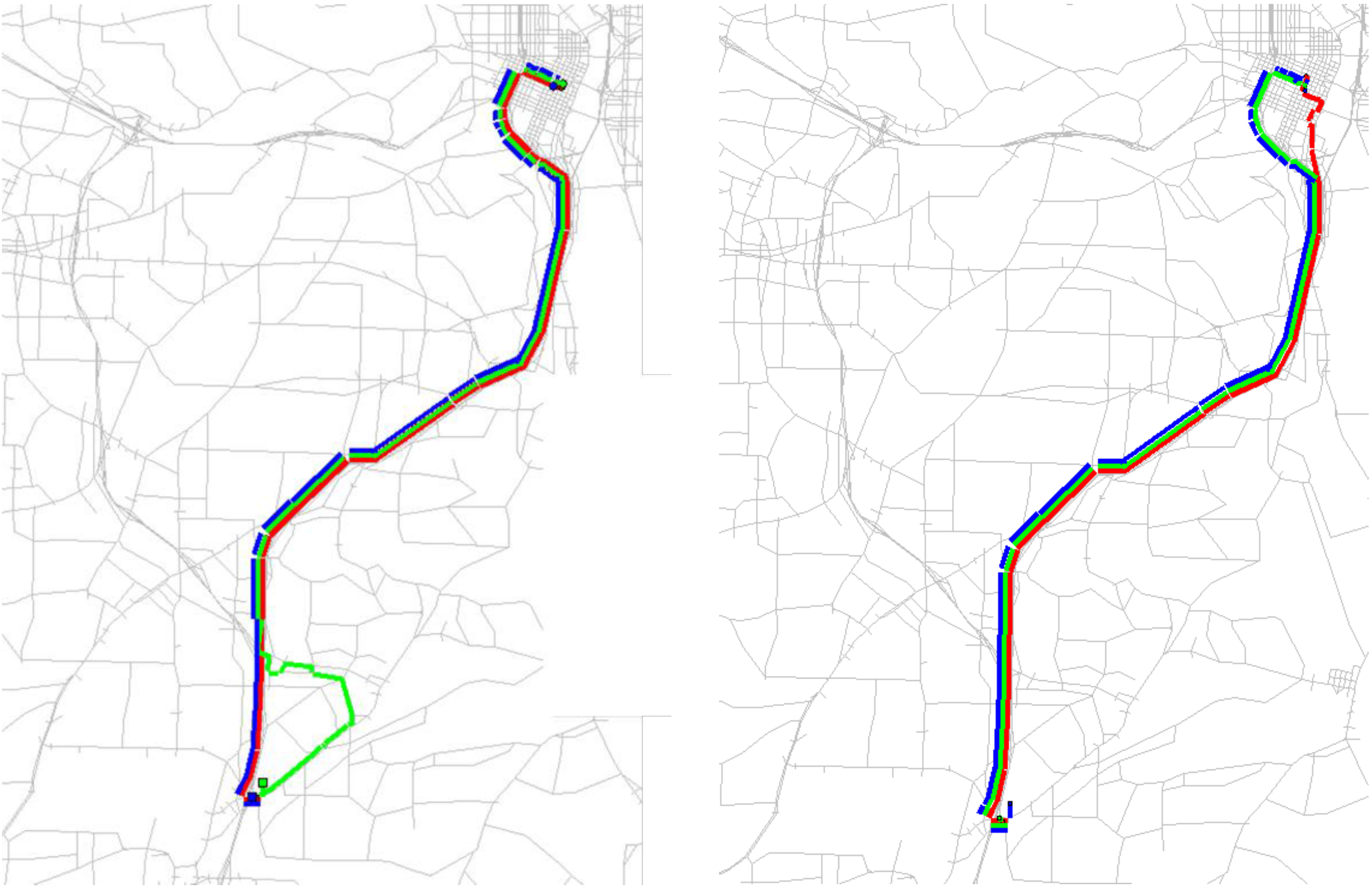
In the BRT in exclusive ROW via added lane case, the dedicated traffic lane improved both the travel time and the reliability for BRT, thus leading to an increase of market share. In the BRT in exclusive ROW via lane removal case, which takes away one automobile lane, the roadway capacity for automobile traffic is significantly reduced, resulting in a higher level of congestion and thus reducing the market share of automobiles.

7.5 Impact of Variable Message Signs on Transit Mode Shares

The general function of VMSs is to provide warning and/or guidance about upstream congestion to alert automobile drivers to the situation and allow them an opportunity to divert to another corridor. This function is particularly useful in the portion of the study area where Barbur Boulevard runs parallel to I-5. When congestion occurs on either highway, the installed VMS helps balance the traffic load on both corridors. This load-balancing mechanism helps alleviate traffic congestion and consequently increases the automobile market share due to improved traffic conditions. As shown in Figure 7.6, the transit market share slightly decreases in all three shown scenarios because VMSs improve traffic conditions for automobiles. This example highlights the market interrelationship between different modes and traffic management strategies. Although seemingly undesirable from a transit operation standpoint, the systemwide total benefit of including both BRT and VMS is properly captured when reliability is incorporated. The effects of reliability in scenario analysis are discussed in Section 7.6.

7.6 Impact of Reliability on Scenario Analysis

Another method for understanding how incorporating reliability measures could affect the scenario analysis outcome is to examine the percentage improvement or change of



(a) Without Reliability (b) With Reliability

Figure 7.2. Route choice options between Portland CBD and Tualatin.

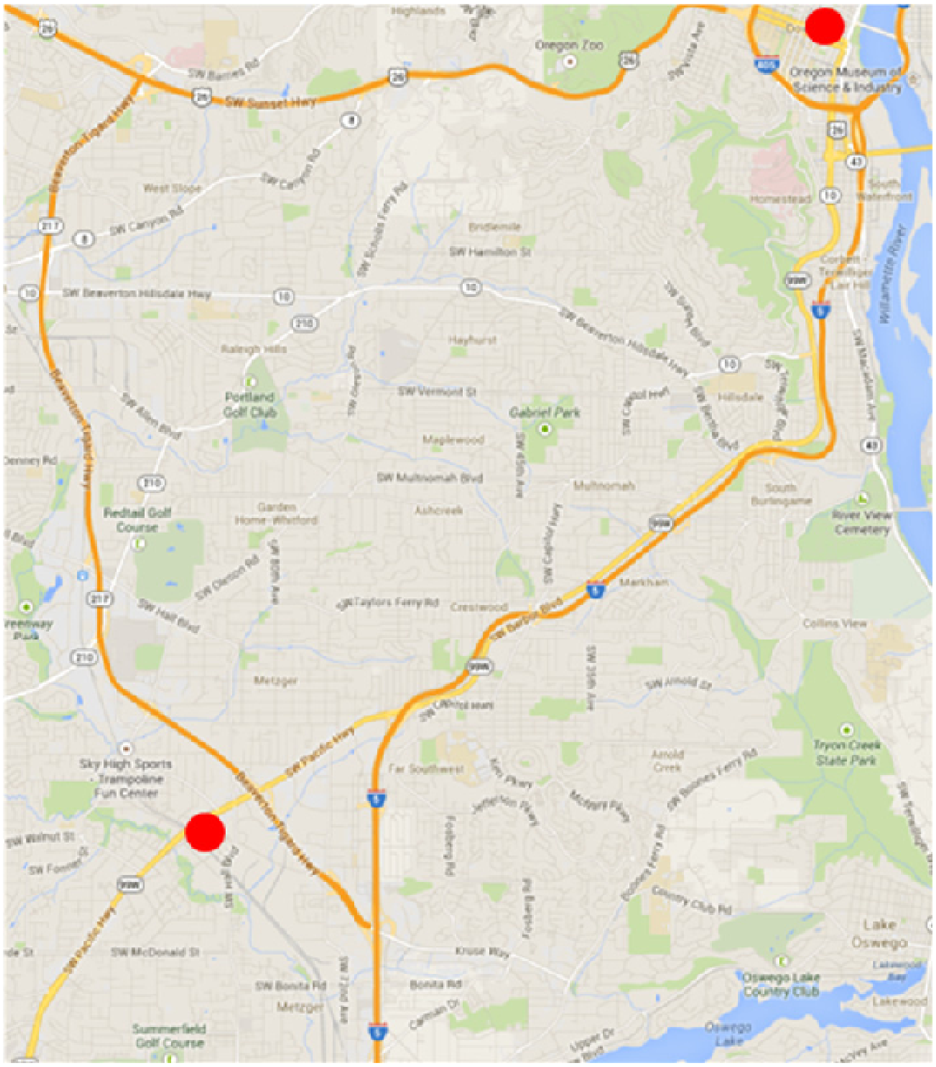
person-based measures of effectiveness (MoEs) [i.e., average travel time, average vehicle miles traveled (VMT), and average delay] across scenarios for cases both with and without reliability. Examining the scenario outcomes based on person-based (in lieu of automobile mode only) MoEs for the entire corridor is the proper way to depict the performance of the study corridor. This approach is of particular importance because most of the studied scenarios are related to BRT operations, and the auto-only MoE does not reflect the actual performance of the scenarios of interest.

Figure 7.7 and Figure 7.8, respectively, illustrate the without reliability and with reliability cases on southbound Barbur Boulevard. The charts on the left-hand side of each figure show the MoE values for each of the three scenarios, and the right-hand charts show the improvement with respect to the baseline case in terms of percentage reduction.

The chart without considering reliability (Figure 7.7) shows that the BRT strategy improved on the baseline case by about 2% in average personal travel time and 7.5% in average delay. For the BRT + VMS case, the improvement in average personal travel time was increased to 4.7% from 2% in the BRT-only case, but the improvement in average delay shrank to 4.7% from 7.5% in the BRT-only case.

Compared to the case without reliability, the main observed difference in the case with reliability on southbound Barbur Boulevard was the increased benefit measures (Figure 7.8). The reduction was 11% for average personal travel time and 11.5% for average delay for the BRT scenario, and 10% and 18.5% improvement for average travel time and delay, respectively, for the BRT + VMS case.

Similar conclusions can be observed for the I-5 corridor (Figures 7.9 and 7.10). Taking southbound as an example, considering the reliability measures increased the benefit of BRT by 15% and BRT + VMS by 20% with respect to average personal travel time and delay. These values are considerably higher than those in the case without considering reliability (2.3% and 5.4%, respectively, for average travel time for BRT and BRT + VMS and 8.5% and 3.6%,



Single Occupancy Vehicle	Total travel time equivalent (min)	Travel time (min)	Travel time equivalent of reliability (min)
Baseline (no reliability)	38	38	0
Baseline (reliability)	48	41	7
BRT in exclusive ROW via add lane (no reliability)	35	35	0
BRT in exclusive ROW via add lane (reliability)	46	40	6

Figure 7.3. Peak-period travel time equivalents between Tigard and Portland CBD.

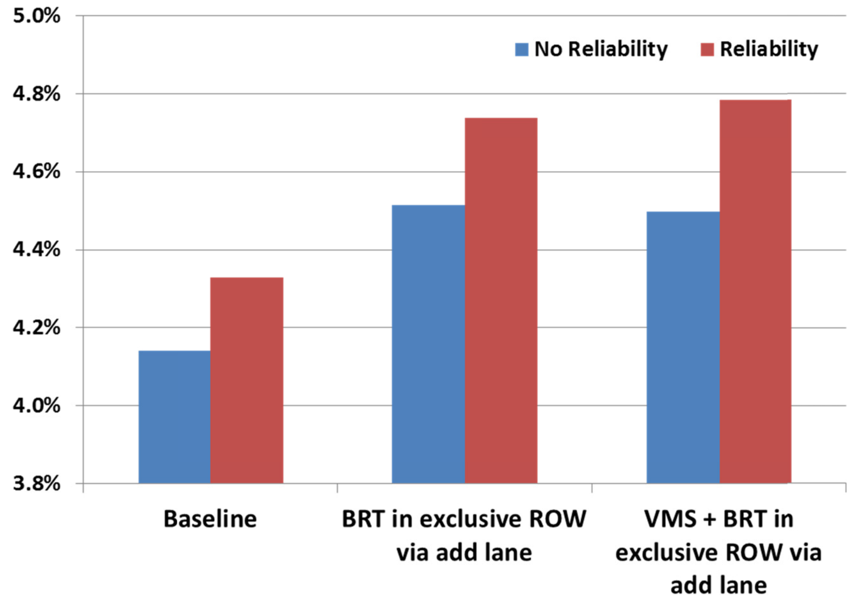


Figure 7.4. Intra–Southwest Corridor transit percentages—comparing scenarios with and without reliability.

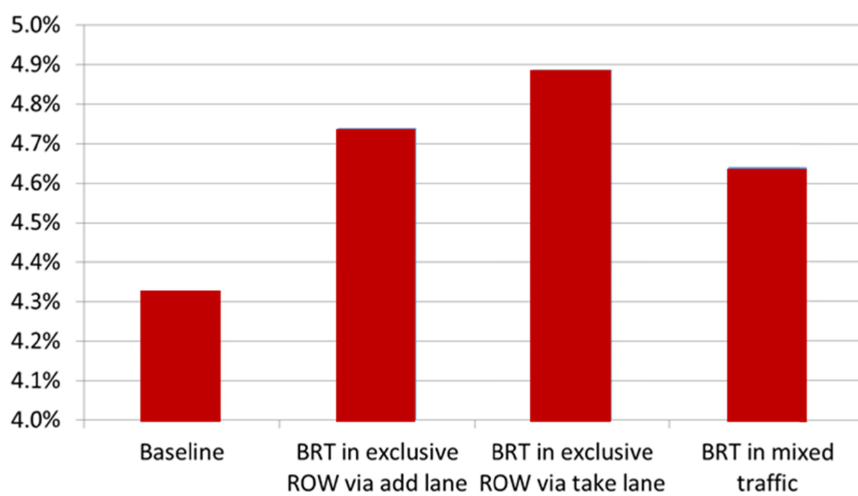


Figure 7.5. Intra–Southwest Corridor transit percentages—all scenarios with reliability.

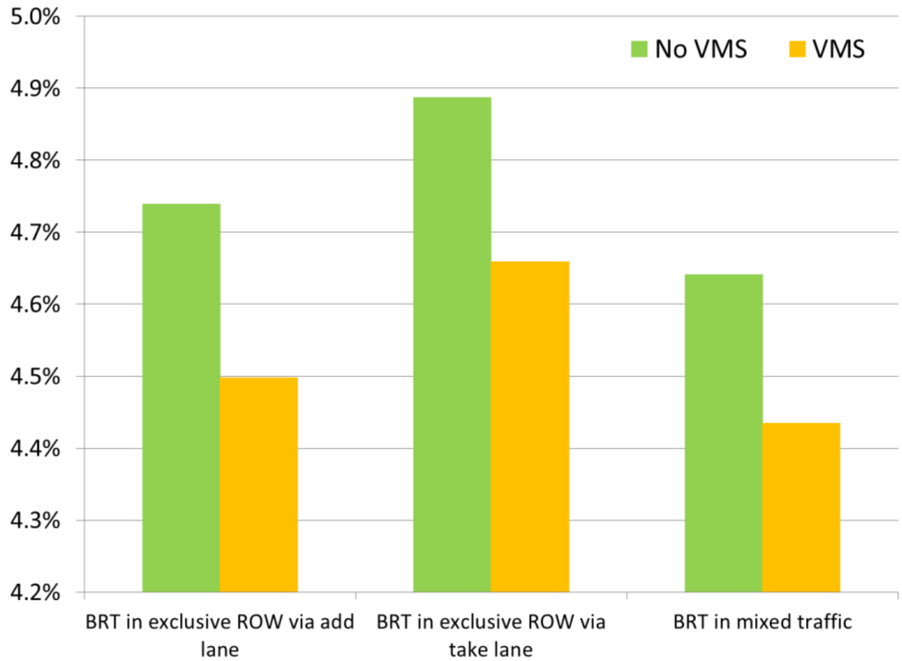
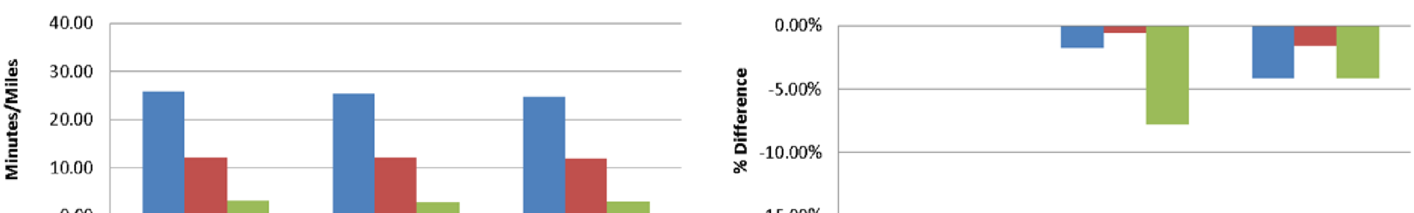


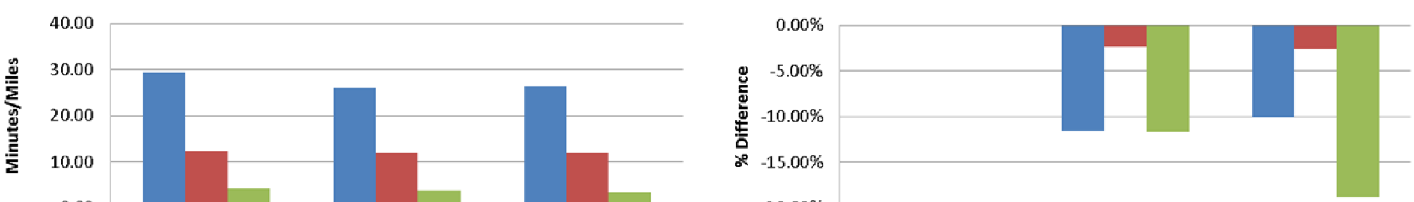
Figure 7.6. Intra–Southwest Corridor transit percentages—comparing all scenarios with reliability, with and without vehicle message signs.



	Baseline	BRT	BRT+VMS
Avg Time	25.83	25.36	24.76
Avg VMT	12.20	12.12	12.00
Avg Delay	3.11	2.87	2.98

	Baseline	BRT	BRT+VMS
Avg Time	0.00%	-1.80%	-4.14%
Avg VMT	0.00%	-0.60%	-1.62%
Avg Delay	0.00%	-7.81%	-4.18%

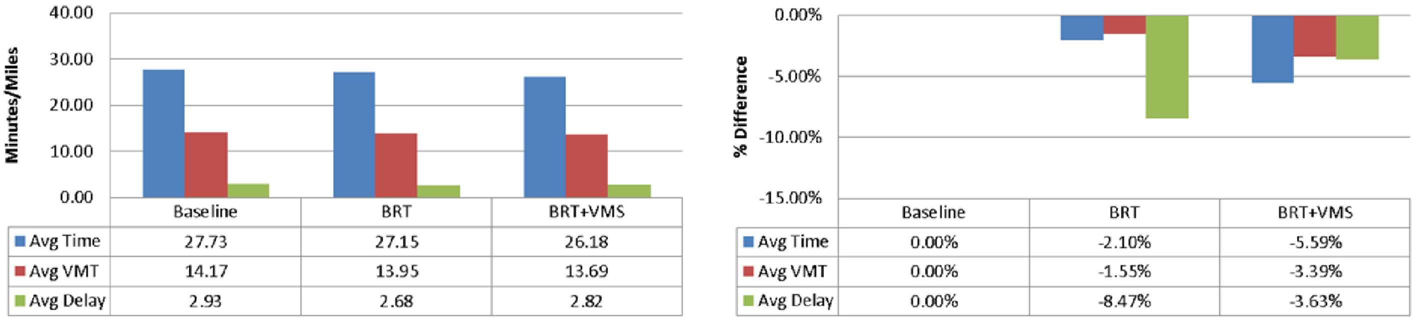
Figure 7.7. Southbound Barbur Boulevard measure of effectiveness (MoE) comparison—without reliability.



	Baseline	BRT	BRT+VMS
Avg Time	29.30	25.93	26.35
Avg VMT	12.29	11.99	11.97
Avg Delay	4.23	3.74	3.44

	Baseline	BRT	BRT+VMS
Avg Time	0.00%	-11.52%	-10.07%
Avg VMT	0.00%	-2.39%	-2.59%
Avg Delay	0.00%	-11.68%	-18.76%

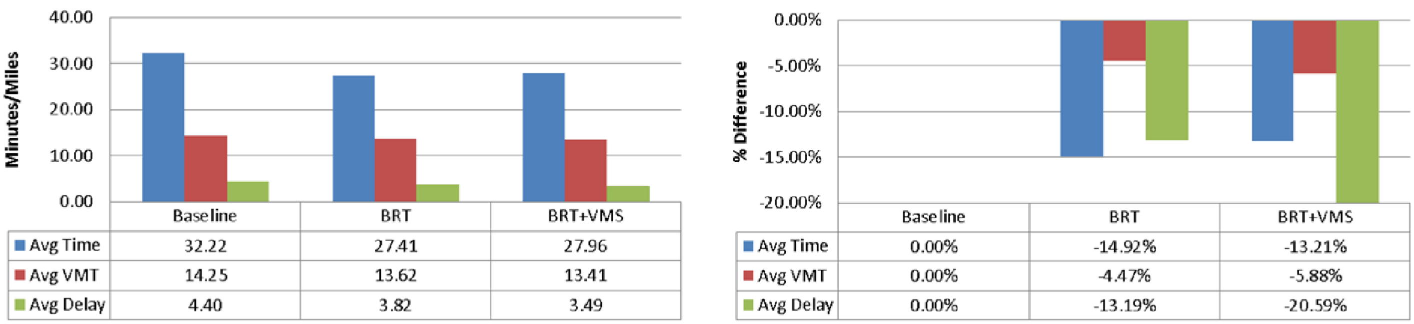
Figure 7.8. Southbound Barbur Boulevard measure of effectiveness (MoE) comparison—with reliability.



	Baseline	BRT	BRT+VMS
Avg Time	27.73	27.15	26.18
Avg VMT	14.17	13.95	13.69
Avg Delay	2.93	2.68	2.82

	Baseline	BRT	BRT+VMS
Avg Time	0.00%	-2.10%	-5.59%
Avg VMT	0.00%	-1.55%	-3.39%
Avg Delay	0.00%	-8.47%	-3.63%

Figure 7.9. Southbound I-5 corridor measure of effectiveness (MoE) comparison—without reliability.



	Baseline	BRT	BRT+VMS
Avg Time	32.22	27.41	27.96
Avg VMT	14.25	13.62	13.41
Avg Delay	4.40	3.82	3.49

	Baseline	BRT	BRT+VMS
Avg Time	0.00%	-14.92%	-13.21%
Avg VMT	0.00%	-4.47%	-5.88%
Avg Delay	0.00%	-13.19%	-20.59%

Figure 7.10. Southbound I-5 corridor measure of effectiveness (MoE) comparison—with reliability.

respectively, for average delay for the BRT and BRT + VMS scenarios).

The increased BRT (exclusive of ROW) benefit that resulted from considering reliability measures can be attributed mainly to the following factors:

1. Including reliability in the route choice for automobile and transit resulted in added impedance (penalty) for both modes. Because automobile travel was less reliable than the BRT option with exclusive ROW in the study corridor, the inclusion of reliability naturally increased the ridership of BRT.
2. The subsequent increased ridership of BRT allowed a higher number of travelers in the corridor using a more reliable BRT mode. Thus, when computing the person-based MoEs for the entire corridor, the results arguably captured the benefit of BRT more accurately than a case with no reliability measure inclusion.
3. The incremental benefit of VMSs was more pronounced when reliability was considered but not the other way around. In other words, when reliability was incorporated the ability of VMSs to properly balance the traffic load between I-5 and Barbur Boulevard in time of congestion could be captured by the model.

CHAPTER 8

Policy-Maker Engagement Workshop

8.1 Second Workshop Summary

The research team organized the second workshop and shared the research findings with the policy group on March 27, 2014, at Portland Metro from 10:30 a.m. to 1:30 p.m. Sixteen attendees participated in this workshop. Attending agencies included the Oregon DOT, Metro (a metropolitan planning organization), City of Tigard, Washington County, City of Sherwood, and City of Portland. Attendees also included two SHRP 2 staff members.

The workshop's participants included the following:

- **Policy Group**
  - TriMet (regional transit authority)
  - Oregon DOT
  - Washington County
  - Metro
  - City of Tualatin
  - City of Portland
  - City of Tigard
- **Workshop Observers**
  - Project supervisory team, Transportation Research Board
  - Metro
- **SHRP 2 L35 Project Team**
  - University of Arizona
  - Metro
  - RST International Inc.

The workshop presented the research outcomes to the policy group by describing the research and by answering the general question "How does reliability measurement affect decision making in the planning process?"

- Overall framework of the research
- Data collection: stated-preference approach to determine value of reliability
- Tool and model building
  - DynusT and reliability calculation
  - FAST-TrIPs and reliability calculation
  - Integration of reliability into the TDM
- Scenario development
- Tool application methodology
  - Schematic
  - Reliability impact on paths

The workshop included open discussions and a consideration of the question "Does information regarding reliability derived in this manner assist you in decision making?" The policy groups listened to all the presented outcomes and engaged in lively discussions about the modeling process and analysis results. The takeaway from the group discussions can be summarized as follows:

- The policy group agreed that this project demonstrated that including reliability in modeling and analyzing various competing investment scenarios was a useful and informative process.
- The sensitivity and order of magnitude of change of model ridership and scenario performance appeared to be intuitive.
- Given the usefulness of the methodology, the next question was how to present reliability-related information to policy makers and the general public. The process of disseminating such methodology and information remains a challenging issue and needs to be addressed in future modeling efforts.
- This methodology can greatly contribute to the cost-benefit analysis for most project analyses. Examples presented in the workshop, like adding a lane or taking an existing lane to accommodate BRT, have significant cost implications, and the results show that the presented methodology has a sufficient level of sensitivity to support a more robust cost-benefit analysis. The value of reliability, which until now could not be communicated in a quantitative manner, needs to be highlighted in the communication with stakeholders.

- Oregon DOT indicated the usefulness of this methodology to help them better quantify the benefit of operations improvement strategies based on a constrained budget.
- The group wanted Metro to undertake a larger-scale stated-preference survey of the entire Metro panel to reconfirm the estimated value of reliability obtained in the earlier phase of this project.
- A policy group member asked about additional resource requirements for an L35A type of study. After the discussions, a consensus was reached that the decision needs to be driven by the modeling needs and questions and that such information should be used to identify the best tool and process to meet the requirements, as well as to justify the time and resource needs for a more sophisticated modeling methodology, such as L35A. Although it took the research team nine months to complete this study, most of the time was spent in the initial model building. Future modeling exercises will require much less time, and the Metro staff has acquired practical experience in this effort. Metro felt studies of this nature are a worthy investment of time and effort for an agency to undertake.
- Current methodology includes a certain relationship between congestion and reliability and to some extent "predicts" reliability based on a travel time measure. It is highly desirable that Metro use actual traffic data acquired from the third-party provider to calibrate the prediction model so that the model can better represent the reliability measure for the Portland region. By doing so, Metro will have a better approach for forecasting future-year reliability.
- The group recognized that rapid advancement of vehicle and communication technologies will effectively reduce highway accidents and consequently reduce this source of unreliability. Nonetheless, the group also recognized the challenges in predicting all future technology-driven improvement and how such advances may affect future impacts on reliability.

8.2 Verifying SHRP 2 L05 Literature Review

Combining the first and second workshop outcomes, the research team also reviewed and verified the literature review reported by the SHRP 2 L05 research team (Cambridge Systematics 2013b). The L35A team's comments regarding the L05 literature review are summarized as follows:

1. The traveler cares about reliability. The L35A team confirmed that this statement has repeatedly been confirmed by policy groups and other research participants.
2. Agencies monitor travel time reliability, but many do not yet use it in planning. The L35A team also confirmed this statement. In the Portland region, the L35A project is the first of this kind of effort to demonstrate the methodology for incorporating reliability into project analysis, and the research team and policy groups reiterated the need for such a methodology, modeling practice, and policy-maker engagement.
3. There are several sources of travel time data for estimating a reliability performance measure. In the Metro region, the agencies have access to Oregon DOT and Metro data that have been collected continuously for years. More recent data from sources such as INRIX or TomTom expand the breadth and depth of data accessibility for Metro.
4. Operations can be incorporated into the planning process. The scenarios analyzed in the L35A project included VMS scenarios. The analysis results demonstrated how that modeling framework and approach exhibit reasonable sensitivity for capturing the performance and benefit of operational strategies. The results of the modeling exercise produced insights about operational strategies.
5. Long-range transportation planning models cannot forecast reliability. The Metro modeling staff and policy group both recognized the limitation of the traditional trip-based planning method.
6. Reliability can be monetized. This L35A research adopted a survey approach that allows an agency to obtain an estimate of the value of reliability in a cost-effective manner. The value of reliability is found to be 0.82 times the value of travel time; this value is comparable to findings in the literature. The proposed method allows an agency to solicit responses through a stated-preference method from a large group of the general traveling public, permitting a cost-effective estimate of a value of reliability measure for the modeling exercise.

CHAPTER 9

Lessons Learned and Concluding Remarks

This project successfully demonstrates viable local methods for estimating reliability measures, as well as the economic value of travel time reliability within a context of transportation decision making.

The principal research activities included (1) increasing policy makers' situational awareness through workshop engagement, (2) obtaining a value of travel time reliability that was locally acceptable for the demonstration needs of this project, (3) applying such a value to an integrated regional TDM and dynamic traffic and transit assignment modeling approach, (4) setting up and evaluating a wide range of scenarios, and (5) presenting the research findings to the same policy groups and obtaining feedback and comments regarding the overall modeling exercise and assessments of potential future use of reliability in actual project analysis.

The Metro policy group adopted a simplified stated-preference method via an online survey to estimate a reliability ratio that could be used to estimate the value of travel time reliability. Although this method is highly simplified, the estimated reliability ratio appears to be comparable with findings in the literature and was confirmed to be acceptable for further project scenario modeling activities.

To better account for the time-varying nature of traffic dynamics and to further leverage prior SHRP 2 research products, the research team applied state-of-the-art network models to capture the needed sensitivity with respect to reliability. The research team integrated Metro's trip-based TDM with the dynamic traffic assignment model DynusT and dynamic transit assignment model FAST-TrIPs. Both of the latter models were based on research products associated with the SHRP 2 C10B project. SHRP 2 L35A is the first project to demonstrate successfully the feasibility of integrating the network models from SHRP 2 C10B with a trip-based model.

More than 10 scenarios were identified and modeled in this project. The analysis results indicated that both bus rapid transit and VMSs would contribute to improved reliability for the Southwest Corridor when considering the performance over multiple modes and facilities. Bus rapid transit contributes to improved corridor performance by increased ridership due to higher reliability, and VMSs contribute to improved corridor reliability by balancing the arterial and freeway flow via information dissemination.

Such modeling processes and results were fully presented and discussed at the second workshop with the Metro policy group. The policy group members concluded that incorporating reliability into the overall scenario and project analysis helped them better understand the potential benefit of studied strategies that could not be realized by using the traditional method.

The research team and the policy group also concluded that a more comprehensive and rigorous survey method with a sufficient number of correspondents will be conducted for the Metro region to establish a value of travel time reliability that can be used in future project selection and policy making.

Multiple paradigms exist for estimating the reliability measures. In addition to L03, an alternate method that can account for more detailed local recurring and nonrecurring data is the Monte Carlo simulation type of method proposed by SHRP 2 L04. The L04 method is applicable to small networks, but it is not useful for a large region due to computational intractability.

CHAPTER 10

References

Balakrishna, R., H. N. Koutsopoulos, and M. Ben-Akiva. 2005. Calibration and Validation of Dynamic Traffic Assignment Systems. In *16th International Symposium on Transportation and Traffic Theory* (H. S. Mahmassani, ed.), College Park, Md., pp. 407–426.

Cambridge Systematics. 2009. *ITS Deployment Analysis System (IDAS) User's Manual.* http://idas.camsys.com/default.htm.

Cambridge Systematics. 2012. *Value of Travel Time Reliability.* Synthesis report and workshop working paper. Cambridge Systematics.

Cambridge Systematics. 2013a. *SHRP 2 Report L03: Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies.* Transportation Research Board of the National Academies, Washington, D.C.

Cambridge Systematics. 2013b. *SHRP 2 Report L05: Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes—Final Report.* Transportation Research Board of the National Academies, Washington, D.C.

Chiu, Y.-C., L. Zhou, and H. Song. 2010. Development and Calibration of the Anisotropic Mesoscopic Simulation Model for Uninterrupted Flow Facilities. *Transportation Research Part B: Methodological,* Vol. 44, pp. 152–174.

Clark, S., and D. Watling. 2005. Modelling Network Travel Time Reliability Under Stochastic Demand. *Transportation Research Part B: Methodological,* Vol. 39, No. 2, pp. 119–140.

Copley, G., P. Murphy, and D. Pearce. 2002. Understanding and Valuing Journey Time Variability. Presented at European Transport Conference, Cambridge, United Kingdom.

Dong, J., and H. S. Mahmassani. 2011. Stochastic Modeling of Traffic Flow Breakdown Phenomenon: Application to Predicting Travel Time Reliability. Presented at 14th International IEEE Conference on Intelligent Transportation Systems, Washington, D.C.

Eliasson, J. 2004. Car Drivers' Valuations of Travel Time Variability, Unexpected Delays and Queue Driving. In *Proceeding of European Transport Conference,* Strasbourg, France.

Eliasson, J. 2009. Reliability in Swedish CBA: Current Practice and What Needs to Be Done. Presented at International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis, Vancouver, B.C., Canada.

Fosgerau, M., and A. Karlstrom. 2010. The Value Reliability. *Transportation Research Part B: Methodological,* Vol. 44, No. 1, pp. 38–49.

Hamdouch, Y., and S. Lawphongpanich. 2008. Schedule-Based Transit Assignment Model with Travel Strategies and Capacity Constraints. *Transportation Research Part B: Methodological,* Vol. 42, No. 7, pp. 663–684.

Hao, J., M. Hatzopoulou, and E. Miller. 2010. Integrating an Activity-Based Travel Demand Model with Dynamic Traffic Assignment and Emission Models. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2176,* Vol. 1, Transportation Research Board of the National Academies, Washington, D.C., pp. 1–13.

Hensher, D. A. 2007. Valuation of Travel Time Savings. In *Handbook in Transport Economics* (R. L. André de Palma, Emile Quinet, and Roger Vickerman, eds.), Edward Elgar Publisher.

Hickman, M. 2001. An Analytic Stochastic Model for the Transit Vehicle Holding Problem. *Transportation Science,* Vol. 35, No. 3, pp. 215–237.

Jayakrishnan, R., H. S. Mahmassani, and T. Y. Hu. 1994. An Evaluation Tool for Advanced Traffic Information and Management Systems in Urban Networks. *Transportation Research Part C: Emerging Technologies,* Vol. 2C, No. 3, pp. 129–147.

Julliffe, J. K., and T. P. Hutchinson. 1975. A Behavioural Explanation of the Association Between Bus and Passenger Arrivals at a Bus Stop. *Transportation Science,* Vol. 9, No. 3, pp. 248–282.

Khani, A., S. Lee, M. Hickman, H. Noh, and N. Nassir. 2012. An Intermodal Shortest and Optimal Path Algorithm Using a Transit Trip-Based Shortest Path (TBSP). Presented at 91st Annual Meeting of the Transportation Research Board, Washington, D.C.

Lam, T. C., and K. A. Small. 2001. The Value of Time and Reliability: Measurement from a Value Pricing Experiment. *Transportation Research Part E: Logistics and Transportation Review,* Vol. 37, No. 2–3, pp. 231–251.

Lin, D.-Y., N. Eluru, T. S. Waller, and C. R. Bhat. 2008. Integration of Activity-Based Modeling and Dynamic Traffic Assignment. Presented at 87th Annual Meeting of the Transportation Research Board, Washington, D.C.

Mahmassani, H. S. 2011. Application to the New York Metropolitan Region of an Integrated Model of User Responses to Pricing and Reliability with a State of the Art Simulation-Based Dynamic Traffic Assignment Tool. N.Y.C. presentation to NYMTC.

MVA. 1996. *Benefits of Reduced Travel Time Variability.* Report. Department for Transport, London.

MVA. 2000. *Etude de l'impact des phénomènes d'irregularité des autobus: Analyse des resultats.* MVA, Paris.

Nava, E., and Y.-C. Chiu. 2012. A Temporal Domain Decomposition Algorithmic Scheme for Large-Scale Dynamic Traffic Assignment. *International Journal of Transportation Science and Technology,* Vol. 1, No. 1, pp. 1–24.

Nguyen, S., and S. Pallottino. 1988. Equilibrium Traffic Assignment for Large-Scale Transit Networks. *European Journal of Operational Research,* Vol. 37, No. 2, pp. 176–186.

Noh, H., M. Hickman, and A. Khani. 2012. Hyperpaths in a Transit Schedule-Based Network. Presented at 91st Annual Meeting of the Transportation Research Board, Washington, D.C.

Northwestern University Transportation Center. 2009. Incorporating Reliability Performance Measures in Evaluation Tools: Physics, Psychology and Economists. Presented at International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis, Vancouver, B.C., Canada.

Peer, S., C. Koopmans, and E. Verhoef. 2009. Predicting Travel Time Variability for Cost-Benefit Analysis. Presented at International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis, Vancouver, B.C., Canada.

Pendyala, R., K. Konduri, Y.-C. Chiu, M. Hickman, H. Noh, P. Waddell, L. Wang, D. You, and B. Gardner. 2012. Integrated Land Use–Transport Model System with Dynamic Time-Dependent Activity-Travel Microsimulation. Presented at 91st Annual Meeting of the Transportation Research Board, Washington, D.C.

Ramjerdi, F., S. Flügel, H. Samstad, and M. Killi. 2010. *Value of Time, Safety and Environment in Passenger Transport: Time.* TØI report 1053B/2010. Institute of Transport Economics, Oslo, Norway.

Sheffi, Y. 1984. *Urban Transportation Networks: Equilibrium Analysis with Mathematical Programming Methods.* Prentice-Hall Inc., Englewood Cliffs, N.J.

Significance, VU University Amsterdam, and John Bates Services. 2013. *Value of Time and Reliability in Passenger and Freight Transport in the Netherlands.* Report for the Ministry of Infrastructure and the Environment, The Hague, Netherlands.

Small, K., C. Winston, and J. Yan. 2005. Uncovering the Distribution of Motorists' Preferences for Travel Time and Reliability. *Econometrica,* Vol. 73, No. 4, pp. 1376–1382.

Spiess, H., and M. Florian. 1989. Optimal Strategies: A New Assignment Model for Transit Networks. *Transportation Research Part B: Methodological,* Vol. 23, No. 2, pp. 83–102.

Taylor, M. A. P. 2009. Reliability and Cost-Benefit Analysis in Australia and New Zealand. Presented at International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis, Vancouver, B.C., Canada.

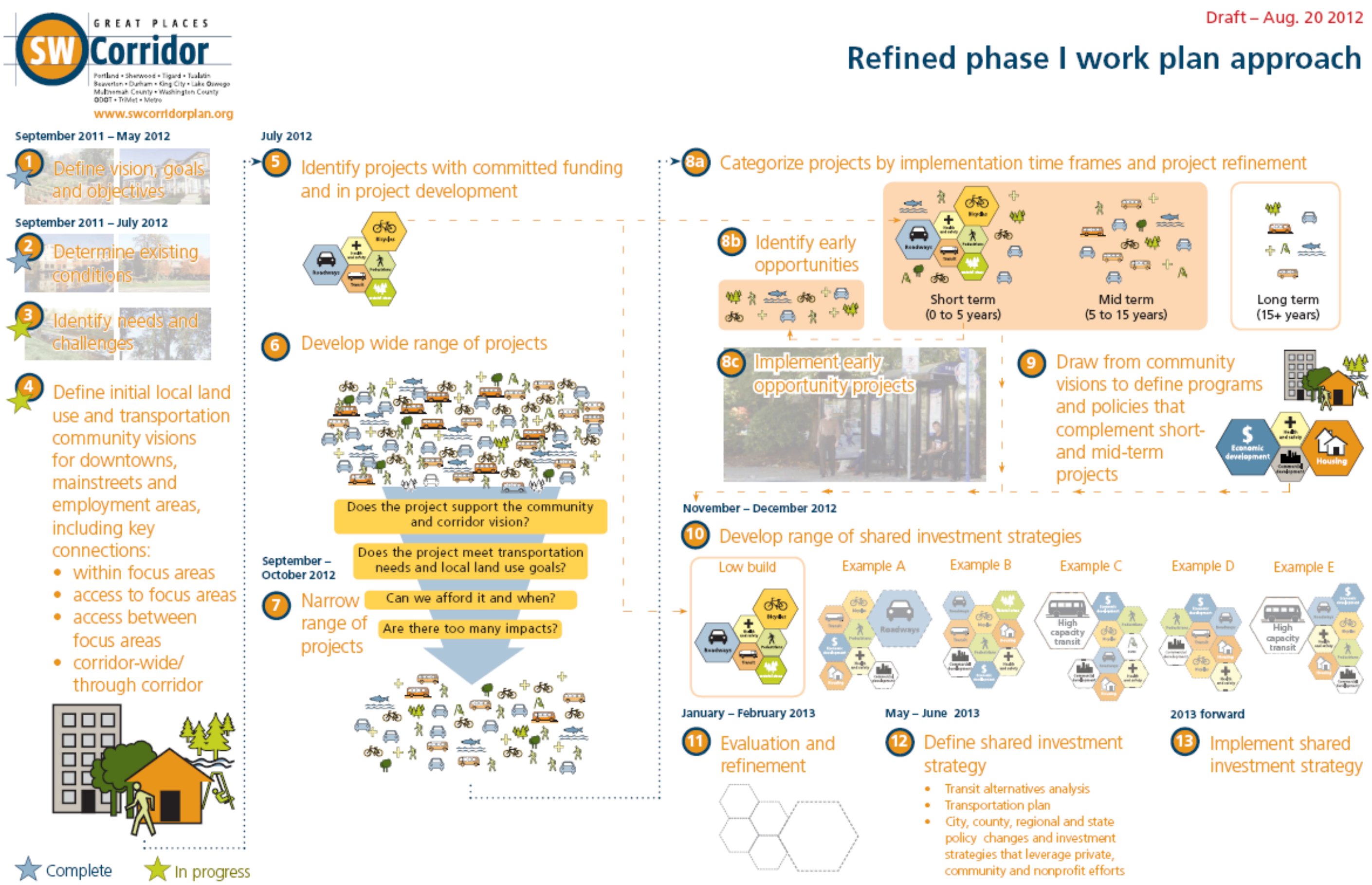
Turning Technologies. 2014. http://www.turningtechnologies.com/.

Van Oort, N. 2011. *Service Reliability and Urban Public Transport Design.* PhD dissertation. Delft University of Technology, Delft, Netherlands.

Vovsha, P. 2009. Reliability in Policy-Sensitive Transportation Models: Insights from SHRP 2. Presented at International Meeting on Value of Travel Time Reliability and Cost-Benefit Analysis, Vancouver, B.C., Canada.

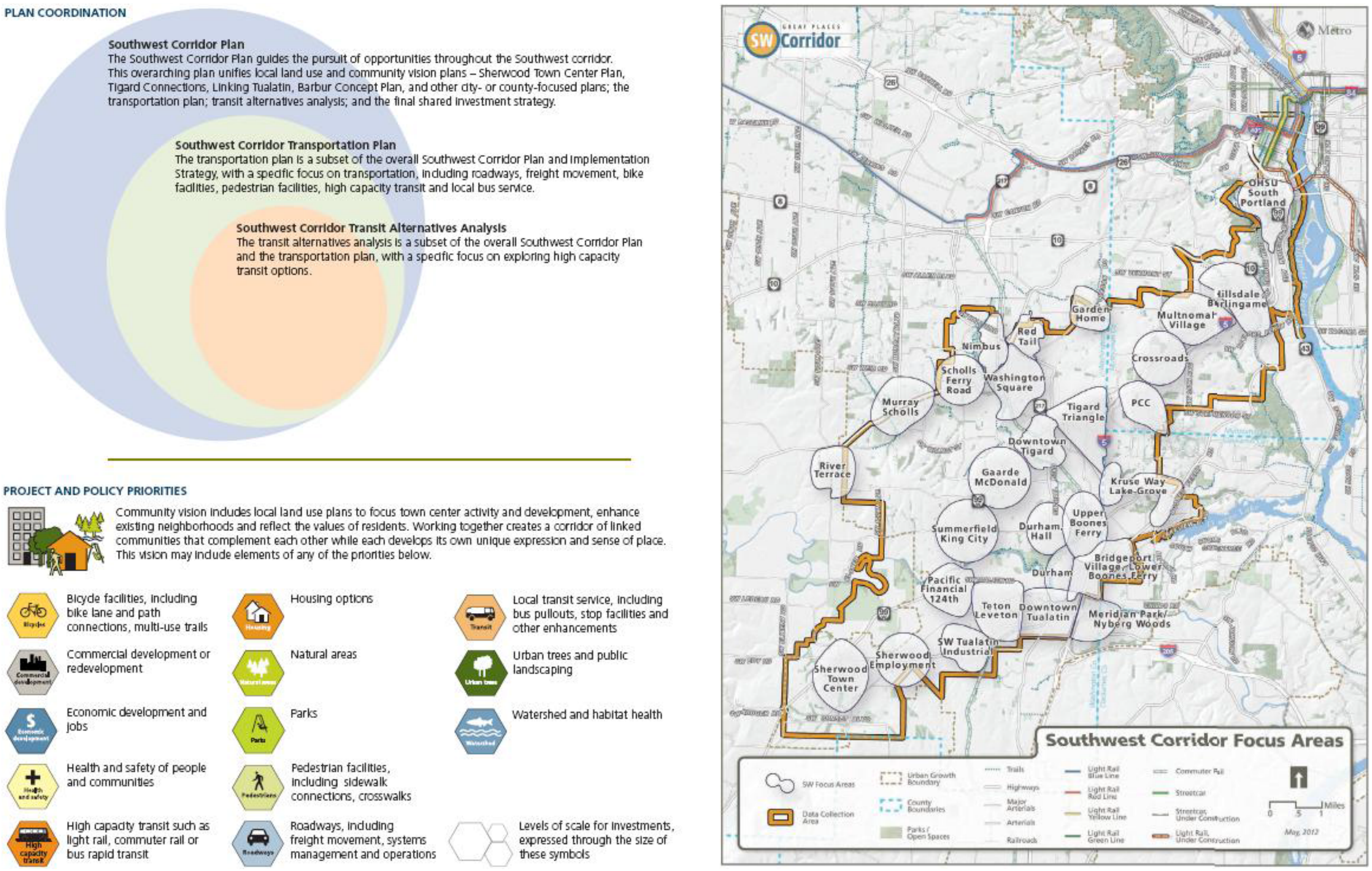
Southwest Corridor Work Plan

Figure A.1 illustrates the Phase 1 work plan approach for the Southwest Corridor, and Figure A.2 describes plan coordination and priorities.



Source: Portland Metro, reproduced with permission.

Figure A.1. Phase 1 work plan approach for the Southwest Corridor.



Source: Portland Metro, reproduced with permission.

Figure A.2. Southwest Corridor Plan details: (*left*) plan coordination and project and policy priorities and (*right*) focus areas.

APPENDIX B

DynusT and FAST-TrIPs Integration Run in DynuStudio

This appendix presents basic procedures to run DynusT–FAST-TrIPs in the DynuStudio environment. Assume all FAST-TrIPs files are located in the same DynusT scenario folder, including all input files, program executables, and integration scripts. All outputs will be saved in the same folder. Figure B.1 shows the DynusT–FAST-TrIPs run window.

- Transit network
  To enable FAST-TrIPs transit, a network must exist and the Transit button must be checked. The Start Time is the transit service starting time in real clock time (min). In Figure B.1, the start time is 11 a.m. or 660 min. The transit dwell times can be set to use the existing values from previous runs or be reset to zero.
- FAST-TrIPs configuration
  Click the FAST-TrIPs button to open DST-FSTRPConfig .dat from the current folder. As shown in Figure B.2, this file contains two parameters:
  - maxIter—maximum number of iterations for the feedback runs; and
  - fstFlag—a flag with a value of 1 or 0 to indicate whether FAST-TrIPs will be run in the integration run. If 0 is given, only DynusT runs will be performed.
- FAST-TrIPs–DynusT feedback
  Check the FAST-TrIPs–DynusT feedback button to enable the integration run, which is controlled by Python script dst_ft_ex.py, which is located in the current scenario folder. The script is composed of the following parts:
  - Execute DynusT run.
  - Execute FAST-TrIPs run.
  - Import dwell times from ft_output_loadProfile.dat and prepare TransitDwellTime.dat to be used in the next DynusT run.
- Import final dwell times
  The final dwell times from FAST-TrIPs can be imported into DynuStudio by using analysis option 20, shown at the bottom of Figure B.3. Figure B.4 shows the transit display option in DynuStudio. After the final dwell times have been imported, they can be displayed in proportional circles at stops on the transit layer as shown in Figure B.5.

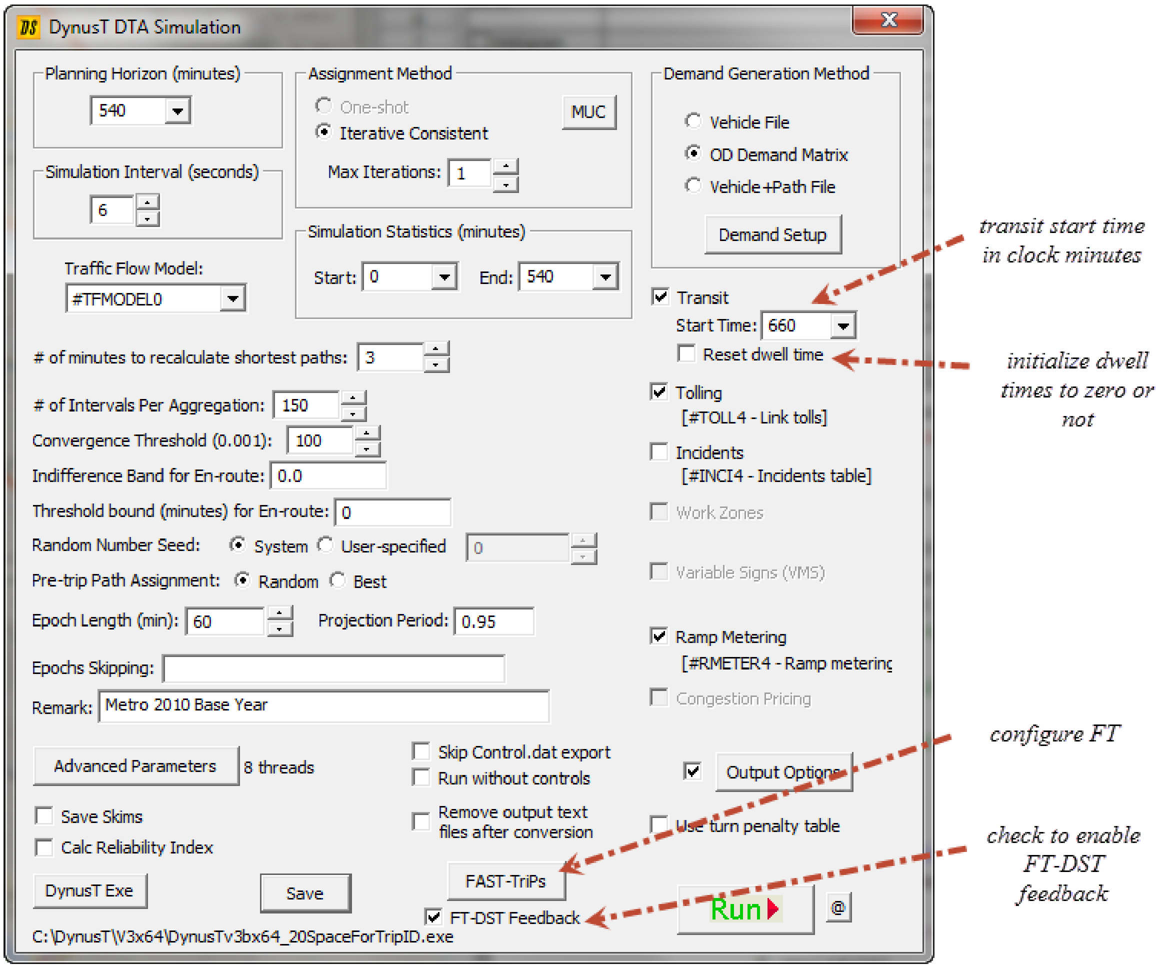


Figure B.1. Run window for DynusT–FAST-TrIPs runs.

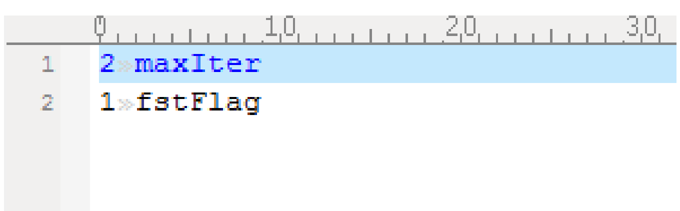


Figure B.2. FAST-TrIPs configuration file.

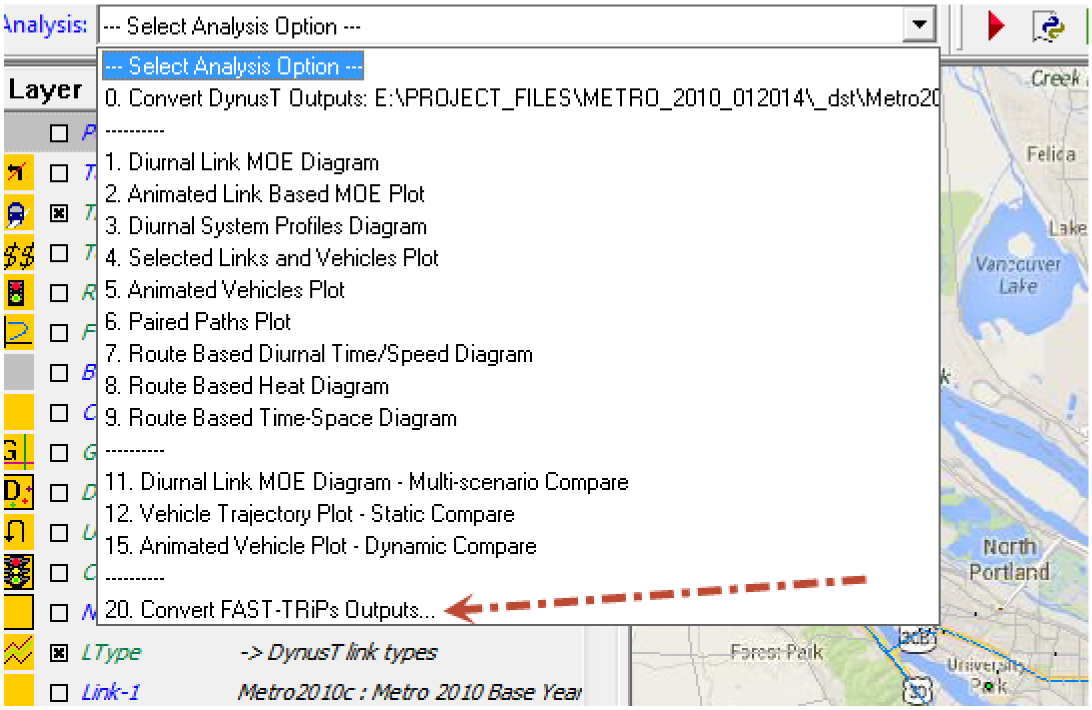


Figure B.3. Analysis options in DynuStudio.

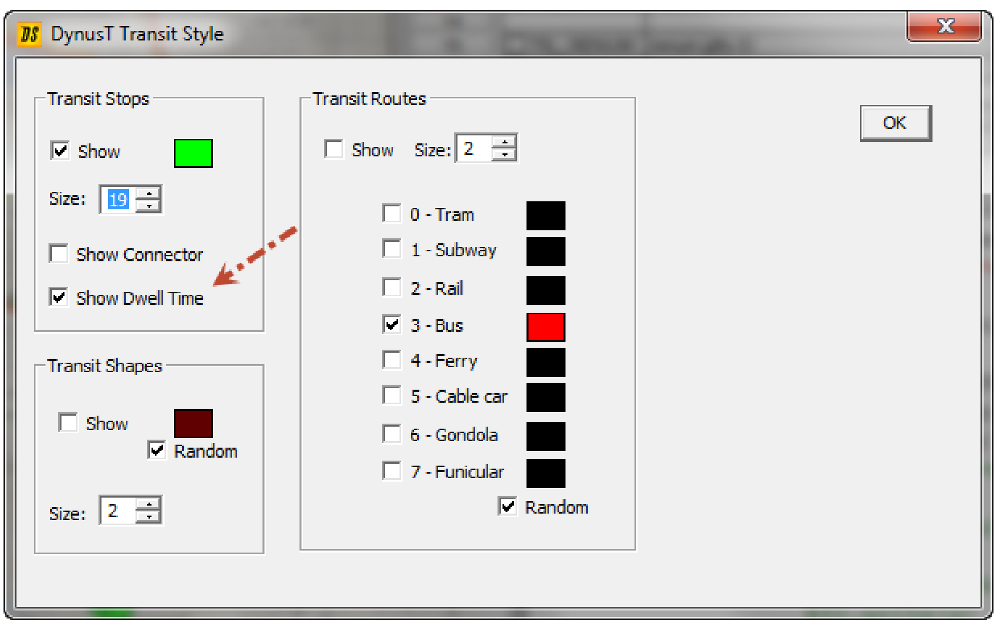


Figure B.4. DynuStudio transit display option.

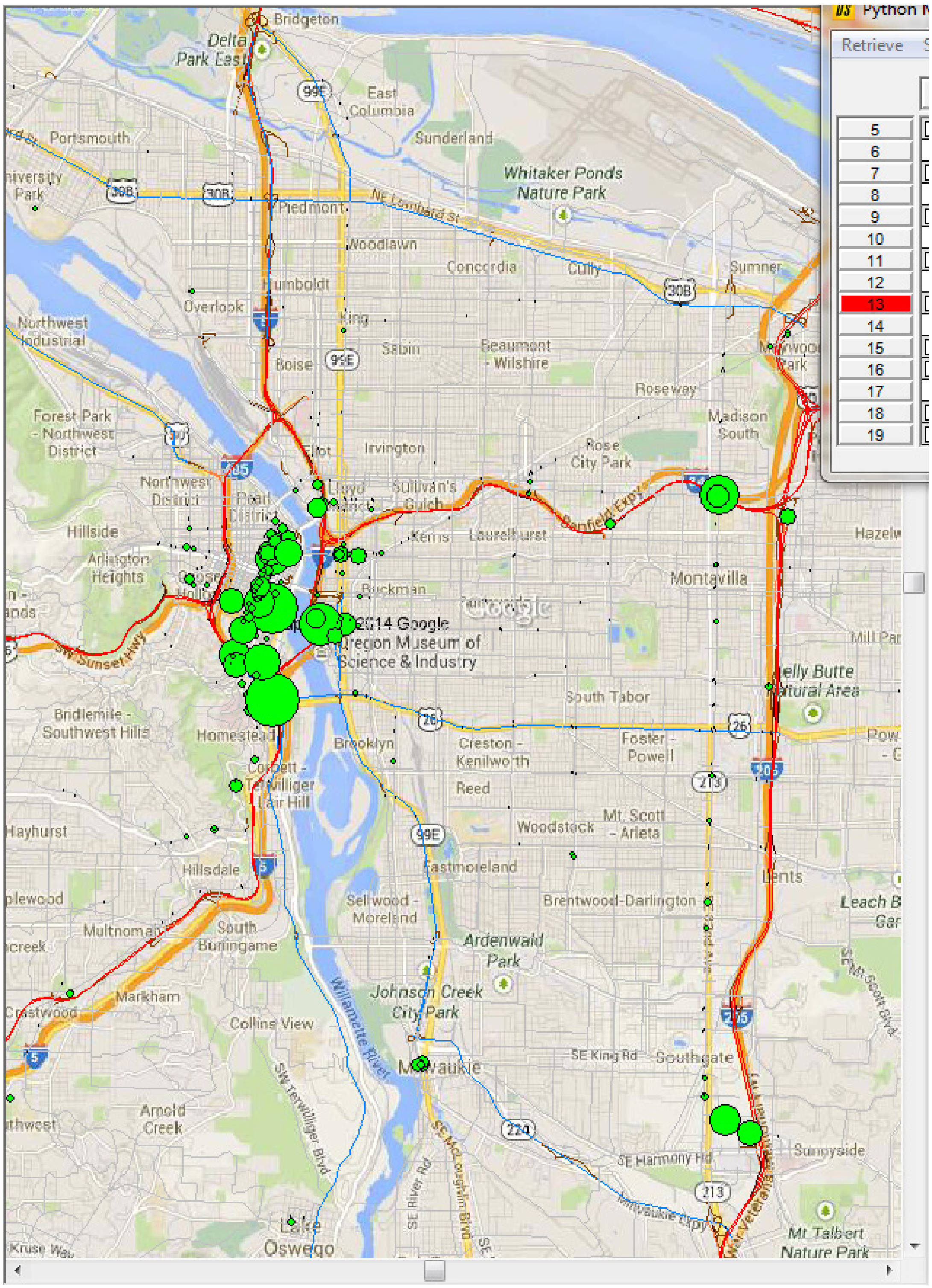


Figure B.5. Transit stops and dwell times indicated by proportional circles.

Related SHRP 2 Research

Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies (L03)

Incorporating Reliability Performance Measures into Operations and Planning Modeling Tools (L04)

Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes (L05)

Identification and Evaluation of the Cost-Effectiveness of Highway Design Features to Reduce Nonrecurrent Congestion (L07)

Value of Travel Time Reliability in Transportation Decision Making: Proof of Concept—Maryland (L35B)

Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand (C04)

Partnership to Develop an Integrated Advanced Travel Demand Model with Mode Choice Capability and Fine-Grained, Time-Sensitive Networks (C10B)