Incorporating Reliability Performance Measures into Operations and Planning Modeling Tools: Application Guidelines

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SHRP 2
STRATEGIC HIGHWAY RESEARCH PROGRAM
Accelerating solutions for highway safety, renewal, reliability, and capacity

Incorporating Reliability Performance Measures into Operations and Planning Modeling Tools

Application Guidelines

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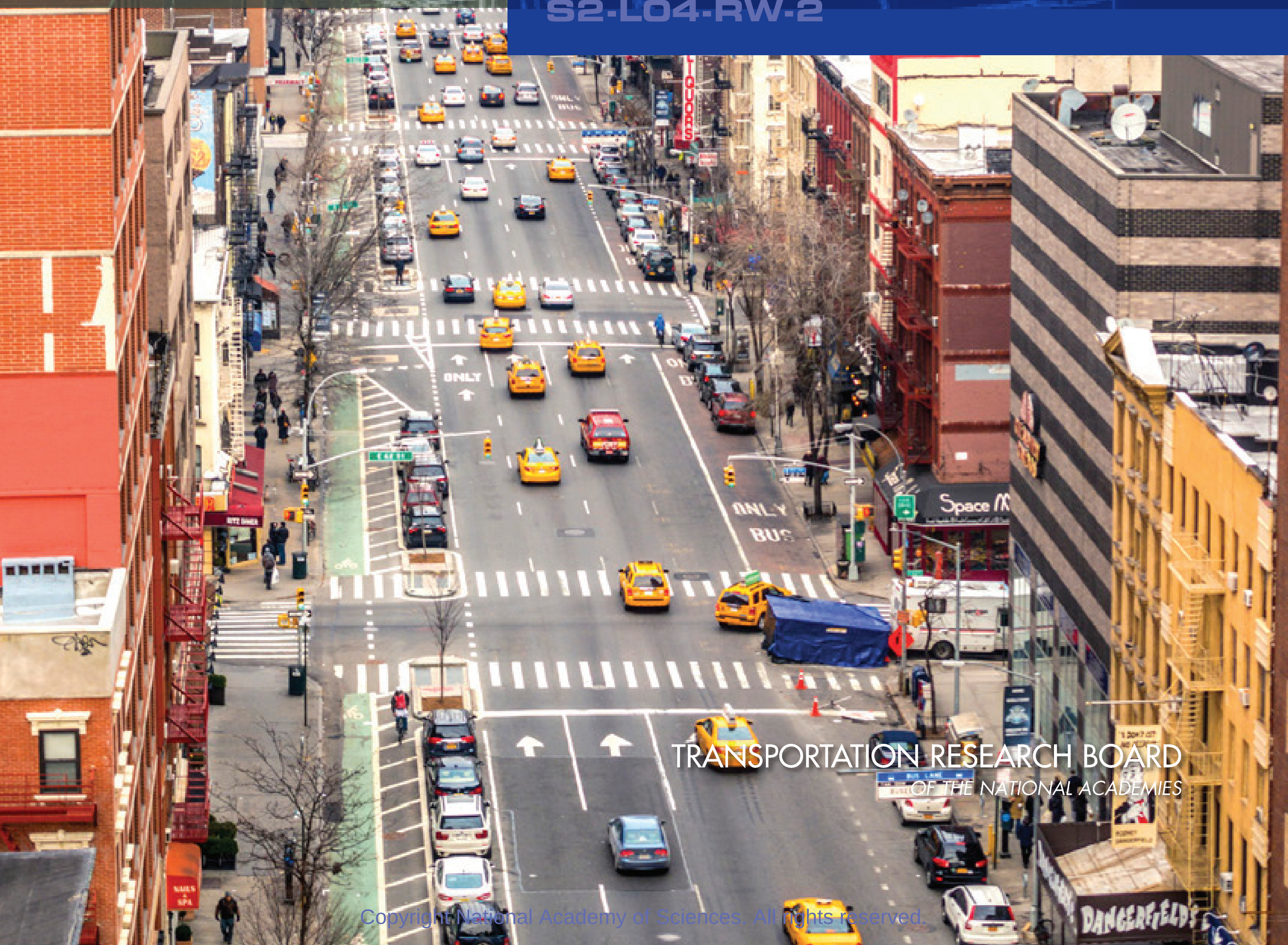

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THE SECOND STRATEGIC HIGHWAY RESEARCH PROGRAM

Incorporating Reliability Performance Measures into Operations and Planning Modeling Tools: Application Guidelines

SHRP 2 Report S2-L04-RW-2

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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

William Hyman
SHRP 2 Senior Program Officer, Reliability

The Incorporating Reliability Performance Measures into Planning and Operations Modeling Tools project explored how to address reliability using micro- and meso-simulation models. In addition, it provided guidance on how to address reliability in other modeling systems, namely in traditional demand forecasting models and with activity-based models coupled with dynamic traffic assignment models. Substantial advances were made in this project, both conceptually and in terms of practical products produced.

This research should be of interest to those concerned with modeling travel time reliability and using the results for transportation system management and operations. The audience for the reports and products resulting from this research includes researchers, planners, traffic engineers, vendors of simulation models, consultants who work hand in hand with transportation agencies, and decision makers concerned with highway operations.

Early in the project the researchers set out a framework for incorporating reliability into planning and operation models that distinguishes between the demand and supply side. Travel demand may be static, as in typical planning models; dynamic for planning and operational models; or activity-based. Supply—in other words, the capacity of each part of the network—may be fixed, stochastic, or systematically varying.

The SHRP 2 Reliability focus area identified seven sources of nonrecurring congestion: incidents, weather, work zones, special events, traffic control devices not working properly, unusual fluctuations in demand, and bottlenecks that can exacerbate these sources of unreliability. These nonrecurring sources of congestion can affect supply, demand, or both; for example, work zones affect supply; special events, demand; and incidents and weather, both. These supply and demand factors influence the travel time for origin–destination (O-D) pairs across the network and, in turn, the distribution of travel time from which various reliability measures can be derived.

To explain how to address reliability when using micro- and mesosimulation models, the framework was extended to distinguish between sources of nonrecurring congestion external (exogenous) to a simulation model and internal (endogenous) to it. Exogenous factors include incidents, weather, and work zones, whereas endogenous factors include heterogeneity of driver behavior and vehicle type on the demand side and breakdown of flow, traffic control, and differences in car-following behavior on the supply side.

Microsimulation models are widely used in the transportation field to understand how vehicles behave in detailed settings, such as a series of traffic signals along an arterial street, freeway onramps, or a small network of roads. Mesosimulation models are suitable for higher-resolution analysis and can be applied to networks of varying sizes, including an entire region. Both micro- and mesosimulation models are based on some form of traffic physics, in contrast to a standard four-step demand model.

This project focused considerable attention on how micro- and mesosimulation models could address travel time reliability. The essence of the approach is to sandwich a simulation model between a pre- and post-processor such that together, all three components can portray travel time reliability on a network or part of it.

The researchers developed two software prototypes that were tested with both a widely used mesosimulation model and a widely used microsimulation model. The first software prototype, the Scenario Manager, consisted of the pre-processor for either type of simulation model. The Scenario Manager produces random scenarios involving various sources of nonrecurring congestion such as traffic incidents, weather, and work zones. It can also address scenarios based on historical data or scenarios previously constructed for planning purposes. The other software prototype is the Trajectory Processor. This post-processor determines the distribution of travel time for every O-D pair on a network. Nearly all the travel time reliability metrics, including standard deviation and the Planning Time Index, can be derived from the travel time distribution. For information about how to use the two prototypes, see their user guides. For more information about the Scenario Manager and the Trajectory Processor, see the project's main report, *SHRP 2 Report S2-L04-RR-1: Incorporating Reliability Performance Measures into Operations and Planning Modeling Tools*.

The research produced this document, *SHRP 2 Report S2-L04-RR-1: Incorporating Reliability Performance Measures into Operations and Planning Modeling Tools: Application Guidelines*, for a micro- or mesosimulation model with pre- and post-processors. Private sector software vendors may wish to closely examine the prototype software to determine the merits of incorporating similar capability into the products they have on the market. The application guidelines and user guides should help private vendors make informed decisions.

It is worth noting that a similar scenario manager and procedures for compiling the distribution of travel time were also developed and applied in the SHRP 2 project Incorporation of Travel Time Reliability into the *Highway Capacity Manual*. The Transportation Research Board Committee on Highway Capacity and Quality of Service approved a motion to incorporate this new approach into the *Highway Capacity Manual*.

The SHRP 2 L04 project also drew on earlier work performed in the SHRP 2 Capacity focus area under a project titled Improving our Understanding of How Highway Congestion and Pricing Affect Travel Demand (SHRP 2 C02). Reliability was introduced into successively richer utility functions, beginning with the traditional variables of out-of-pocket costs and travel time, and progressively adding other variables including travel time reliability. The researchers describe how to place a value on travel time reliability given other relevant terms in the utility function and emphasize that the value of reliability is not a constant; rather, it varies with such factors as vehicle occupancy and household income. This project on incorporating reliability into planning and operation models absorbed important aspects of the earlier research performed within the SHRP 2 Capacity focus area.

Finally, a substantial effort was undertaken within this project to provide guidance on how to integrate reliability into a modeling system that uses activity-based models on the demand side and a fine-grained, time-sensitive model on the supply side (e.g., a mesosimulation model). This guidance appears in the project's reference material report (*SHRP 2 Report S2-L04-RR-1: Incorporating Reliability Performance Measures into Operations and Planning Modeling Tools: Reference Material*).

CONTENTS

1 INTRODUCTION

This document provides an overview of the methodology and tools that can be applied to existing microsimulation and mesoscopic modeling software to assess travel time reliability. The methodology is primarily based on research, and the tools have been developed only at the prototype stage. However, through rigorous testing at different levels of simulation resolution, the framework, the processes, and the tools have been shown to have practical applicability for use by transportation agencies and consultants for policy and project evaluation.

Moving beyond the potential applications, one measure of this project's success would be the adoption of the framework by one or more simulation modeling vendors. Incorporating the principles of the framework and processes into future versions of their proprietary software would lead to wider use of travel time reliability; transportation professionals could easily apply these new metrics in their project and policy evaluation processes that employ particle-based traffic simulation models.

DOCUMENT OBJECTIVE

The objective of this document is to provide an overview of where and how the methodologies, processes, and tools developed in this SHRP 2 project can be applied. Specifically, the application guidelines provide

- A description of the practical applications at both the policy and project level;
- A systematic description of the various steps involved in applying the travel time reliability methodology, including an overview of the associated tools and how they function in conjunction with the simulation models; and
- Demonstrated evidence of how the methodology can be applied.

With regard to the final point, Chapter 7 discusses two case studies that demonstrate how the framework and tools can be applied to potentially real-life transportation planning/engineering situations.

TRAVEL TIME RELIABILITY APPLICATIONS IN OPERATIONS-ORIENTED MODELS

The process developed for incorporating travel time reliability into traffic modeling tools has multiple applications in the traffic operations and planning environment, in which particle-based traffic simulation modeling tools producing individual vehicle trajectories are employed. The potential uses generally fall within two broad categories: policy-based analysis and project-based analysis. A general description of the possible applications under these categories follows.

Policy-Level Applications

At the policy level, metropolitan planning organizations (MPO) or other agencies responsible for planning the road component of the transportation network need to understand the current or future status of the road network in a particular urban or rural environment. Travel time reliability, which is depicted in the form of descriptive statistics derived from the distribution of travel times, provides an excellent indication of the operating conditions of any road network. Other performance metrics, such as network travel time or average travel time along key routes, do not fully capture and convey the trend in the operating status of an entire road network.

The framework developed as part of this project enables the use of various travel time reliability metrics to better describe the status of the road network overall. Policy makers can use a mesoscopic model in a large network or a microscopic model in a smaller network to assess the overall road network by applying the framework for incorporating travel time reliability into operations models. Tests of the network can be conducted using different sources of unreliability, including systematic factors affecting travel time (such as recurring congestion due to inadequate base capacity). Further reliability tests of the network can be conducted by assessing exogenous sources of variability such as weather, incidents, and other disruptive events.

Under a baseline assessment of the network, in which various tests have been conducted according to the application of the Scenario Manager, reliability indicator results from the Trajectory Processor may show significant variation in travel times. [For more information about the Scenario Manager and the Trajectory Processor, see *SHRP 2 Report S2-L04-RR-1: Incorporating Reliability Performance Measures into Operations and Planning Modeling Tools* (Mahmassani et al. 2014).]

These findings may indicate that policy makers need to put in place new or modified policies to improve the travel time reliability results. These changes may involve policy levers such as travel demand management, road pricing strategies, improved traffic management and traffic control strategies, additional roadway capacity, or improvements to other modes to effect a mode shift away from vehicular traffic.

Building on that networkwide policy application, online and real-time applications may also present promising opportunities to improve the supply of traveler information and, specifically, the relative reliability of alternative routes in a congested network. Most users of a road network in a congested urban area have grown accustomed to the increase in travel time that occurs during the peak periods because of higher demand and limited capacity. However, the unknown variability in travel times due to both endogenous and exogenous sources is a factor that most users cannot readily accommodate in their trip planning. Most users, in planning a trip, want information for making route choice decisions that, even though resulting in longer travel times during the peak periods, offers an acceptable level of stability or reliability. The provision of travel time reliability information, in near real time, would increase the value of the supplied information to travelers.

Current advanced traffic management systems (ATMS) have already incorporated the use of near-real-time predictive modeling to assess various traffic management strategies before actual implementation in the field. Through this predictive modeling process, travel time reliability could be a further measure that can be added to the modeling process, given that particle-based simulation models are currently being employed. The operations models would need to recognize the dynamic and probabilistic nature of traffic flow, compute travel time reliability online, and disseminate this information to the traveling public in real time through the traveler information system component of the ATMS. The framework for incorporating travel time reliability into operations modeling tools would derive the current level of reliability, with the output producing the travel time information, reliability of travel time, most reliable path, and least cost path for the routes being managed under the ATMS. Such a framework has been demonstrated in prototype form by Dong and Mahmassani (2009) and its benefits for both individual travelers and the overall system shown through simulation.

Project-Level Applications

At the project level, practitioners apply numerous metrics to measure the performance or effectiveness of an improvement option compared with a base case or a relative comparison to other options as part of the overall evaluation process to identify a preference. Level of service, travel speeds, travel time savings, operating cost savings, and vehicle miles traveled are typical metrics for comparing improvements to the transportation network. However, in congested urban areas, some of these metrics are inappropriate measures of traffic operations. Furthermore, the majority of the analysis is based on road networks operating under optimal conditions, free of any factors that may influence travel time reliability. For a comprehensive evaluation, practitioners may wish to include travel time reliability in the list of metrics used in project option evaluations.

For example, traffic control or geometric changes in a road network (such as a road widening project along a particular corridor with multiple options) could easily be tested by applying the travel time reliability framework developed in this project. Using the Scenario Manager, tests could be designed with unreliability sources such as weather and/or incident probabilities as per the available study area data. The tests could also be designed to examine travel time reliability over a particular area of the road network or just within the corridor being modified. From multiple runs and the output from the Trajectory Processor, an appropriate travel time reliability index could be used to illustrate the level of travel time reliability for each road configuration option. These travel time reliability results would be used in the comparative evaluation of the options, thus assisting in the selection of a preferred option.

Another project-level related application is the testing of networks under planned event conditions, such as construction work zones, festivals, sporting events, and major concerts. A planned event may include changes to the network supply, such as road or lane closures, as well as changes in the base daily travel demand and/or variations in travel patterns. The process of incorporating travel time reliability into operations models developed in this study can be applied to assess the performance of the network under planned event conditions.

To understand the effects of the planned event, the base network operating conditions first need to be characterized. Using the framework and modeling tools, a series of tests can be designed to assess the reliability of the base network and several key routes. The effects of the planned event on the base network can then be assessed by using the reliability framework. That is, various tests can be designed through the Scenario Manager to include the supply side changes (spatially and temporally) as well as the anticipated changes in travel demand as obtained from model runs using a parent travel demand forecasting model. The travel time reliability output from the Trajectory Processor can be compared with the base case scenario to identify the changes in travel time reliability and, if specifically included in the analysis, which routes have been affected.

If the effects of a planned event are deemed unacceptable without any interventions, further tests can be designed using the Scenario Manager and the simulation model to investigate the use of various mitigation strategies, including traffic control changes, rerouting options through the use of variable message signs (VMS), and alterations to the network supply in the form of reversible lanes. For best results and improved functionality, the "reliability-aware" operations models need to be able to represent work zones and mitigation strategies such as VMS decision-based routing.

2 TRAVEL TIME RELIABILITY INDICES

Various studies have identified a number of reliability performance measures and provided recommendations on their suitability for different purposes. Lomax et al. (2003) defined three broad categories of reliability performance indicators and discussed a variety of measures based on these concepts: (1) statistical range, (2) buffer time measures, and (3) tardy trip indicators. The authors suggested three specific indicators—percent variation, Misery Index, and Buffer Time Index—as promising measures that provide consistent analytical conclusions.

The National Cooperative Highway Research Program (NCHRP) Report 618 (Cambridge Systematics, Inc. et al. 2008) provides guidance on selecting measures for different purposes and types of analyses. The reliability measures recommended by that study include Buffer Index, percent on-time arrival, Planning Time Index, percent variation, and 95th percentile.

The SHRP 2 Project L03 (Cambridge Systematics, Inc., et al. 2013) conducted an extensive empirical study and pointed out some shortcomings of the performance metrics recommended by previous studies. For example, the 95th percentile travel time may be too extreme to reflect certain improvements introduced by traffic operations strategies, but the 80th percentile would be useful in such cases. Also, for performance indicators that measure the distance between central and extreme values (e.g., Buffer Index), the median would be a more robust central tendency statistic than the mean because travel time distributions are by nature skewed. Based on such modifications, the study recommended six reliability metrics: Buffer Index, failure/on-time measures, Planning Time Index, 80th percentile Travel Time Index, skew statistic, and Misery Index.

Although many previous studies have focused on corridor- or link-level travel time reliability, this project aims to perform a full range of analysis addressing network-level, origin–destination–level (O-D–level), path-level, and segment- or link-level travel time reliability using regional planning and operations models. Users need to consider not only the different properties of the reliability measures (as investigated in the studies mentioned in the preceding paragraphs) but also their applicability to an intended analysis level. Table 2.1 presents a list of available reliability measures, categorized on the basis of their applicability to different levels of travel time distributions and associated reliability analysis, namely, network level, O-D level, path/segment level, and link level.

For the network level, travel times experienced by vehicles are not directly comparable because distances traveled by vehicles may be significantly different. In this case, measures that are normalized by the trip distance can be used. Each vehicle's travel time can be converted into the distance-normalized travel time (i.e., travel time per mile, or TTPM), and various statistics can be extracted from the distribution of TTPMs as presented in Type A measures in Table 2.1. For the O-D level, travel times experienced by vehicles are comparable—although actual trip distances could be different depending on the route followed by each vehicle. The O-D–level travel times are not limited to travel times between actual traffic analysis zones (TAZ). Travel time distributions between any two points can be included in this category. Reliability measures that can be used when travel times are comparable include many conventional metrics, such as the mean and standard deviation of travel times, percentiles, and the Buffer Index, as presented in Type B in Table 2.1. For O-D–level analysis, therefore, both Type A and Type B measures can be used. At the path/segment/link level, not only are the travel times for different vehicles comparable but trip distances are also the same. This allows the calculation of the unique free-flow travel time for a given path and, therefore, allows the use of additional measures that require the free-flow travel time. Such measures include Travel Time Index, Planning Time Index, Misery Index, and frequency of congestion as shown in Type C in Table 2.1. Thus, users can use any of Type A, B, and C measures for the path/segment/link-level travel time reliability analysis.

TABLE 2.1. RELIABILITY MEASURES FOR DIFFERENT ANALYSIS TYPES

		Analysis Level		
		Network	**O-D**	**Path/Segment/Link**
Characteristic	**Travel times for vehicles**	Not comparable	Comparable	Comparable
	Travel distances for vehicles	Different	Different	Identical
Applicable Measures	**Distance-normalized measures** (Type A)	• **Mean of travel time per mile (TTPM)** • **Standard deviation of TTPMs** • **95th/90th/80th percentile TTPM**		
	Measures for comparable travel times (Type B)		• **Average travel time** *Standard deviation of travel times* • **Coefficient of variation** *Standard deviation of travel times/mean travel time* • **95th/90th/80th percentile travel time** • **Buffer Index** *(95th percentile travel time – mean travel time)/mean travel time* • **Skew Index** *(90th percentile travel time – median travel time)/(median travel time – 10th percentile travel time)* • **Percent on-time arrival** *Percentage of travel times < 1.1 × median travel time*	
	Measures for the same travel distance (Type C)			• **Travel Time Index (TTI)** *Mean travel time/free-flow travel time* • **Planning Time Index (PTI)** *95th percentile travel time/free-flow travel time* • **Misery Index** *Mean of the highest 5% of travel times/free-flow travel time* • **Frequency of congestion** *Percent of travel times > 2 × free-flow travel time*

3 CONCEPTUAL FRAMEWORK

Incorporating reliability into operations modeling tools entails three main components. (1) The Scenario Manager captures exogenous unreliability sources such as special events, work zones, and travel demand variation. (2) Reliability-integrated simulation tools model sources of unreliability endogenously, including user heterogeneity, weather effects, flow breakdowns, and so forth. (3) The vehicle Trajectory Processor extracts reliability information from the simulation output, namely, vehicle trajectories. Accordingly, the methodological framework for incorporating reliability into stochastic network simulation models is shown in Table 3.1.

Figure 3.1 illustrates how the three components constitute the unifying framework for the scenario-based reliability analysis. The Scenario Manager provides an environment for developing scenarios to capture the exogenous sources of uncertainty, such as external events, traffic control and management strategies, and travel demand–side factors. Using these generated scenarios in conjunction with the historical average demand as inputs, the traffic simulation models produce the vehicle trajectory outputs. During the simulation, the traffic simulation models capture the endogenous sources of travel time variability, such as endogenous flow breakdown and collision, heterogeneous driving behaviors, and so on. The resulting vehicle trajectories are then processed in the Trajectory Processor to obtain travel time distributions and to extract various reliability performance measures. Figure 3.1 also shows possible feedback loops (shown in dotted lines); they imply that the simulation outputs, which could be either scenario-specific or aggregated over multiple runs, might affect the scenario generation scheme in the Scenario Manager and update basic inputs like the average travel demand.

TABLE 3.1. METHODOLOGY FRAMEWORK

Input (exogenous sources)	**Scenario Manager**	
	Demand • Special events • Day-to-day variation • Visitors • Closure of alternative modes	*Supply* • Incidents • Work zones • Adverse weather
Simulation model (endogenous sources)	**Existing Simulation Tools with Suggested Improvements**	
	Demand • Heterogeneity in route choice and user responses to information and control measures • Heterogeneity in vehicle type	*Supply* • Flow breakdown and incidents • Heterogeneity in car following behavior • Traffic control • Dynamic pricing
Output	**Vehicle Trajectory Processor**	
	• Travel time distribution • Reliability performance indicators • User-centric reliability measures	

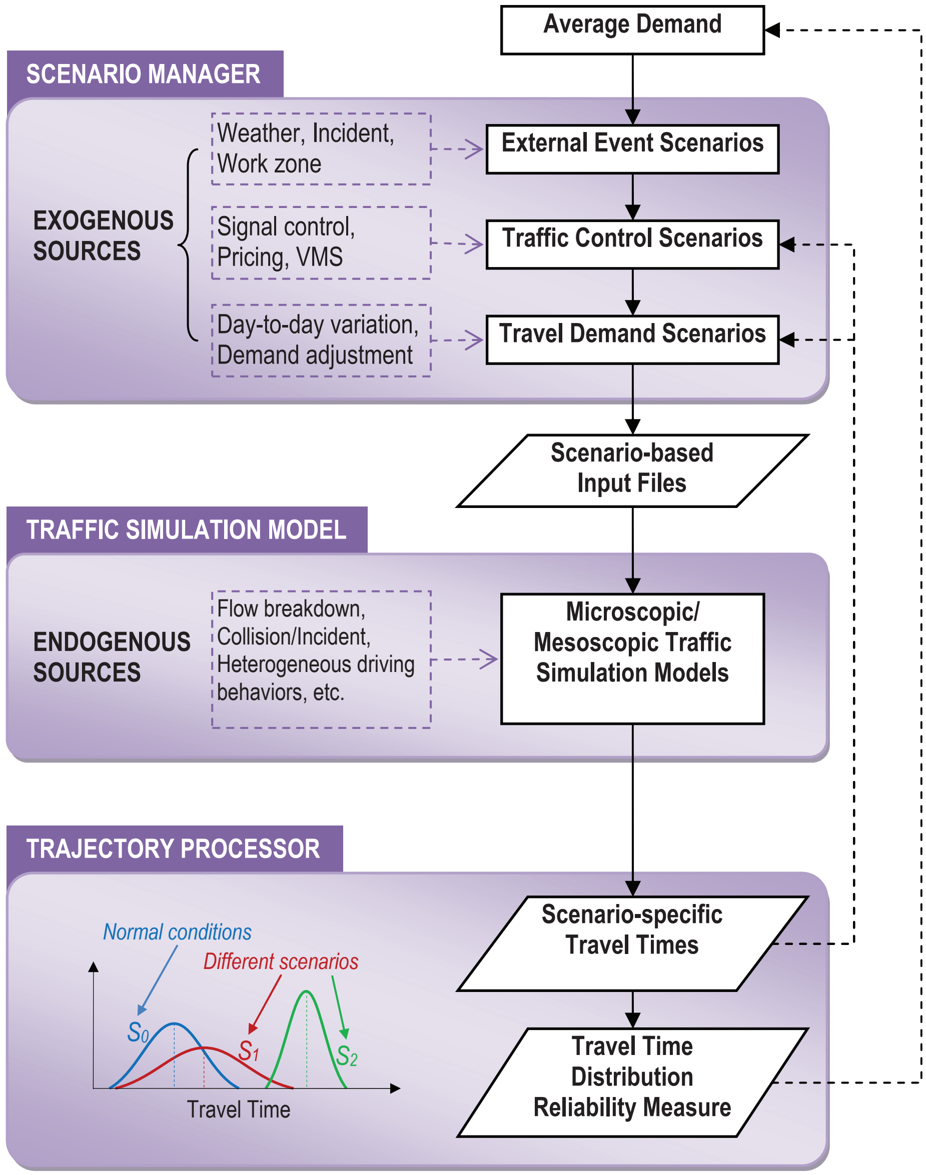


Figure 3.1. *Process for scenario-based reliability analysis.*

4 ANALYSIS TOOLS AND DATA

The travel time reliability analysis framework incorporates two essential tools that provide the capability to produce reliability performance measures as output from operational planning and simulation models. The Scenario Manager, an integral component of the overall analytical framework, captures external unreliability sources such as special events, adverse weather, and work zones, and generates appropriate files as input into simulation models. The other key analysis tool is the vehicle Trajectory Processor, which calculates and visualizes travel time distributions and associated reliability indicators (such as 95th percentile travel time, Buffer Time Index, Planning Time Index, frequency that congestion exceeds some threshold) at link, path, O-D, and network levels.

The travel time distributions and associated indicators are derived from individual vehicle trajectories, defined as a sequence of geographic positions (nodes) and associated passage times. These trajectories are obtained as output from particle-based microscopic or mesoscopic simulation tools. Such trajectories may alternatively be obtained directly through measurement [e.g., global positioning system (GPS)–equipped probe vehicles], thus enabling validation of travel time reliability metrics generated on the basis of output from simulation tools.

Note that both the Scenario Manager and the Trajectory Processor have been developed at a prototype level of detail and functionality for project team use only and are shared with the developer and user community on an "as is" basis. For this reason, they may not meet all requirements of an implementing agency without further development.

A prerequisite for the use of these analysis tools is the availability of a particle-based traffic simulation model, capable of producing vehicle trajectory output. It is further assumed that the simulation model is fully calibrated to reasonably simulate traffic flows. For demonstration purposes, the Scenario Manager and Trajectory Processor prototypes incorporate interfaces to the Aimsun and DYNASMART-P simulation platforms, as examples of microscopic and mesoscopic tools, respectively.

SCENARIO MANAGER

The Scenario Manager is essentially a preprocessor of simulation input files for capturing exogenous sources of travel time variation. Recognizing the importance of the scenario definition and the complexity of identifying relevant exogenous sources, the Scenario Manager provides the ability to construct scenarios that entail any mutually consistent combination of external events. These may be both demand- and supply-related events, including different traffic control plans which may be deployed under certain conditions. Accordingly, it captures parameters that define external sources of unreliability (such as special events, adverse weather, and work zones) and enables users either to specify scenarios with particular historical significance or policy interest, or to generate them randomly given the underlying stochastic processes with specific characteristics (parameters) following a particular experimental design.

The built-in Monte Carlo sampling functionality allows the Scenario Manager to generate hypothetical scenarios for analysis and design purposes. When used in that manner (i.e., in random generation mode), the Scenario Manager becomes the primary platform for conducting reliability analyses, as experiments are conducted to replicate certain field conditions under both actual and hypothetical (proposed) network and control scenarios. In particular, the Scenario Manager enables execution of experimental designs that entail simulation over multiple days, thus reflecting daily fluctuations in demand, both systematic and random.

The Scenario Manager also allows users to manage the conduct of reliability analyses by providing an environment for storage and retrieval of previously generated scenarios, through a scenario library approach. The scenario management functionality allows retrieval of historically occurring scenarios or of previously constructed scenarios as part of a planning exercise (e.g., in conjunction with emergency preparedness planning). Given a particular scenario, the Scenario Manager's main function is to prepare input files for microscopic or mesoscopic simulation models. In addition, the Scenario Manager can facilitate direct execution of the simulation software for a particular scenario by creating the necessary inputs that reflect the scenario assumptions.

An especially important and interesting feature of a well-configured Scenario Manager is that it can be tied into an area's traffic and weather monitoring system(s). In that way, particular scenario occurrences could be stored when they materialize, with all applicable elements that define that scenario, especially demand characteristics and traffic control plans triggered for that scenario. For example, if Houston experiences major rainfall with extensive flood-like conditions, that scenario could be stored in terms of the event and the exogenous parameter values. Using a properly configured Scenario Manager interfaced with the data warehousing system at a given traffic management center, the system operator could extract the relative occurrence probabilities and distribution functions, which would then allow calibration of these external event scenarios to actual observations. Considerable sophistication and functionality could be introduced in such a process over time—as the historical data records increase in quantity, quality, and completeness—and allow robust estimation of occurrence probabilities of otherwise infrequent events.

TRAJECTORY PROCESSOR

The vehicle Trajectory Processor is introduced to extract reliability-related measures from the vehicle trajectory output of the simulation models. It produces and helps visualize reliability performance measures (travel time distributions, indicators) from observed or simulated trajectories. Independent measurements of travel time at link, path, and O-D levels can be extracted from the vehicle trajectories, allowing for the construction of the travel time distribution.

From the system operator's perspective, reliability performance indicators for the entire system allow comparison of different network alternatives and policy and operational scenarios. This could facilitate decision making in regard to actions intended to control reliability and evaluation of system performance. Reliability measures (such as 95th percentile travel time, Buffer Time Index, Planning Time Index, frequency that congestion exceeds some expected threshold) can be derived from the travel time distribution or, alternatively, computed directly from the travel time data.

In addition to the reliability performance indicators, it is essential to reflect the user's point of view, as travelers will adjust their departure time, and possibly other travel decisions, in response to unacceptable travel times and delays in their daily commutes. User-centric reliability measures describe user-experienced or perceived travel time reliability, such as probability of on-time arrival, schedule delay, and volatility and sensitivity to departure time. In particular, to quantify user-centric reliability measures, the experienced travel time and the departure time of each vehicle are extracted from the vehicle trajectory. By comparing the actual and the preferred arrival time, the probability of on-time arrival can be computed.

DATA REQUIREMENTS

This section provides a brief discussion of the types of data needed to implement the proposed reliability analysis framework. This discussion assumes that a base simulation model is already developed and properly validated, and it focuses on (a) data required for the development of scenarios for reliability analysis, and (b) data required to refine/adapt the simulation model and/or to perform travel time reliability analysis based on observed congestion conditions.

As indicated, numerous external factors can affect variations in travel time. To consider these factors in the comprehensive methodology, extensive background data are required. These include collision data, weather data, and event data encompassing lane closures, work zones, and other incidents affecting normal traffic flow. In addition, historical vehicle traffic volumes and background travel demand for other scenarios are important for simulating events that may cause changes in travel patterns or the overall level of traffic demand. Desirable data also include trajectory data from GPS or other probe vehicle sources. These data can be processed to provide valuable information regarding actual trip travel times (portions of trips) through the study area, thus allowing comparisons to simulated data.

Data for Scenario-Based Analysis

The reliability analysis framework addresses a number of sources of travel time variability under both recurring and nonrecurring congestion conditions, whether these affect the demand or supply side of the transportation system, in a random or systematic manner, endogenously or exogenously to the involved modeling tools.

In general, data are needed to set parameters for the factors that will be captured endogenously in the models, whether on the demand or supply side of the system. For example, speed, flow, and occupancy data can be used to describe characteristics relevant to flow breakdown conditions (jam density, and so forth); location, time, and pricing applicable by vehicle class and type [truck, bus, high-occupancy vehicle (HOV), single-occupancy vehicle (SOV)] are needed to incorporate dynamic pricing schemes; event logs and observed or estimated compliance rates may also be needed to capture user responses to information and control measures.

For the proposed scenario-based analysis in particular, data are needed to generate scenarios for factors causing travel time variability due to supply-side changes that need to be addressed exogenously to the models through the Scenario Manager. Such data should include information about incidents (ideally including severity of incident and length of time), special events (type, location, time/date, duration), weather conditions, and work zones. In addition, before-after studies for major planned events can be helpful. Similarly, and depending on the scenarios to be addressed in the reliability analysis, data are needed for the Scenario Manager to address demand-side changes (e.g., attendance at a special event, visitors to a special place, or closure of alternative modes).

Table 4.1 provides a summary of data that could be used to generate scenarios for certain exogenous factors. Such data are typically available through the transportation authorities that manage, control, or simply monitor transportation systems in an area, or through other third parties (e.g., meteorological service for weather conditions) if additional detail is needed for modeling purposes.

TABLE 4.1. TYPICAL DATA REQUIREMENTS FOR DEVELOPMENT OF SCENARIOS FOR TRAVEL TIME RELIABILITY ANALYSIS

Event Type	Data Requirements
Incident	• Type (e.g., collision, disabled vehicle) • Location • Date, time of occurrence, and time of clearance • Number of lanes/shoulder and length of roadway affected • Severity in case of collision (e.g., damage only, injuries, fatalities) • Weather conditions • Traffic data in the area of impact before and during the incident (e.g., traffic flows; speed, delay, travel time measurements; queues; and other performance measures or observations, if available)
Work zone	• Work zone activity (e.g., maintenance, construction) that caused lane/road closure, and any other indication of work zone intensity • Location and area/length of roadway impact (e.g., milepost), number of lanes closed • Date, time, and duration • Lane closure changes and/or other restrictions during the work zone activity • Weather conditions • Special traffic control/management measures, including locations of advanced warning, speed reductions • Traffic data upstream and through the area of impact, before and during the work zone (e.g., traffic flows and percentage of heavy vehicles; speed, delay, travel time measurements; queues; and other performance measures or observations, if available) • Incidents in work zone area of impact
Special event	• Type (e.g., major sporting event, official visit/event, parade) and name or description • Location and area of impact (if known/available) • Date, time, and duration • Event attendance and demand generation/attraction characteristics (e.g., estimates of out-of-town crowds, special additional demand) • Approach route(s) and travel mode(s) if known • Road network closures or restrictions (e.g., lane or complete road closures, special vehicle restrictions) and other travel mode changes (e.g., increased bus transit service) • Special traffic control/management measures (e.g., revised signal timing plans) • Traffic data in the area of impact before, during, and after the event (e.g., traffic flows; speed, delay, travel time measurements; queues; and other performance measures or observations, if available)
Weather	• Weather station identification or name (e.g., KLGA for the automated surface observing system station at LaGuardia Airport, New York) • Station description (if available) • Latitude and longitude of the station • Date, time of weather record (desirable data collection interval: 5 minutes) • Visibility (miles) • Precipitation type (e.g., rain, snow) • Precipitation intensity (inches per hour, liquid equivalent rate for snow) • Other weather parameters (temperature, humidity, precipitation amount during previous 1 hour, if available)

Trajectory Travel Time Data and Sources

The specific analysis approach in the proposed reliability evaluation framework requires a special type of travel time data, which was not available until recent technological developments made its collection possible. In particular, the requirement for trajectory-based travel times for individual vehicles, which are analyzed over their time and space dimensions and various aggregate metrics, may almost exclusively be satisfied by vehicle probe-based data.

Because the proposed reliability evaluation framework is based on travel times reported (and/or estimated) on a per vehicle trajectory basis, the travel time data required to support this research need to satisfy the following trajectory information requirements:

- Report travel times by vehicle trip on a trajectory basis; at a minimum provide *X-Y* coordinates and time stamp at each reported location;
- Capture both recurring and nonrecurring congestion on a range of road facilities (from freeways to arterial roads and possibly managed lanes);
- Represent sufficient sampling and time-series to allow statistically meaningful analysis; and
- Provide the ability to tie travel time data to other ancillary data for time variability sources (to allow parameterization for simulation testing purposes, as discussed earlier).

Furthermore, the trajectory data should ideally possess the following general characteristics for travel time reliability analysis:

- Capture both types of congestion (recurring and nonrecurring).
- Cover the range of road facilities that may be included in the subject area analysis, from freeways to arterial roads and (possibly) managed lanes.
- Allow statistically meaningful analysis of data through availability for a relatively long time period (e.g., a time frame that is long enough to cover seasonal variation).
- Provide travel time at disaggregated levels (e.g., vehicle travel time) and at fine time intervals (e.g., link/path travel time for every 5 minutes), in addition to average travel times, to capture time-of-day variation and vehicle-to-vehicle variation.
- Provide sufficient information on components, causes, and other characteristics of congestion, so that appropriate parameterization can be established for simulation testing purposes.

The emergence of vehicle probe data over the past few years has created the opportunity to capture all necessary information for this type of analysis, since such data can be available all the time for all major roads in the network, including major arterials. Probe-based trajectory data represent a significant increase in the quality and quantity of relevant information. The detail in such data makes it possible to analyze travel time data according to network and route components (e.g., on link and path basis) as well as according to geographic aggregations (e.g., on O-D zone basis).

5 USING THE TOOLS

The scenario-based reliability analysis framework developed under this project aims to provide a systematic and unifying way to incorporate travel time reliability into the decision-making process in traffic operations and planning. The roles and functions of the Scenario Manager and the Trajectory Processor within this framework have been discussed in the previous chapters. This chapter outlines the overall steps for implementing the framework using these tools, and it provides a brief discussion of general approaches to performing each step. The basic steps addressed in this chapter are (1) scoping the study, (2) scenario definition, (3) design of simulation experiments, and (4) output analysis.

SCOPING THE STUDY

To develop the scope of the study, the problem or objective must first be defined. Defining the problem includes identifying the scale or spatial magnitude of the problem, which in turn determines the type of analysis to be applied. This analysis type could be networkwide, corridor-specific, segment, or other. The spatial magnitude of the problem may also determine the simulation resolution to be applied.

In addition to the spatial limits, the temporal boundaries should be defined such that any analysis focuses on the specific problem whether it is related to a weekday peak period or to a weekend special event.

Acquisition of relevant data is also fundamental to properly assess the reliability impacts associated with the network, corridor, segment, and so on. Depending on the problem at hand, specific data may be required to create the various testing scenarios. Data related to the various exogenous factors affecting travel time reliability need to be acquired to populate the scenario manager, again depending on the problem to be analyzed. These additional data could include road closure information, collision data, weather data, special event data, and so on. The data to be collected would correspond to the spatial and temporal limits defined earlier.

SCENARIO DEFINITION

Travel time reliability is a relative concept in that it depends on the temporal and spatial boundaries for which travel times are observed. For example, the travel time reliability for weekdays is different from that for weekends on the same road network. Therefore, defining the applicable time and space domains (i.e., temporal horizon and geographic scope) is an essential first step for any study. In general, the time domain is specified by a date range of the overall time period (e.g., 6/1/2012 to 8/31/2012), day of week (e.g., Monday to Friday), and time of day (6 a.m. to 10 a.m.); or it could be a specific season or day of each year (e.g., Thanksgiving Day). The space domain defines the level for which travel time data are collected and the reliability measures calculated (e.g., network level, O-D level, path level, and link level).

Once space and time domains are defined, the next step is to identify factors that affect travel time distributions for the given domains. Various supply- and demand-side factors can be considered as scenario components that define input scenarios for traffic simulation. Figure 5.1 depicts examples of supply-side factors: weather, planned special events, work zone, incident, and traffic management and control. Figure 5.1 also provides examples of demand-side factors: day-to-day demand random variation and temporary demand surge due to a certain special event.

Once a user determines the factors to be included as scenario components, the next step is to construct actual scenarios that will be simulated using traffic flow models. In this study, the term *scenario* represents a collection of various event instances of supply- and demand-side factors; each event instance can be represented by a set of attributes specifying when (time), where (location), and how (intensity) it occurs, as illustrated in Figure 5.2. Each scenario represents a possible daily situation on a given network. The user defines a set of input scenarios either by generating random scenarios using the Scenario Manager's Monte Carlo sampling capability or by using deterministic scenarios from the existing historical scenarios.

An important issue in generating scenarios is to consider dependencies between different factors. As represented by the dotted arrows in Figure 5.1, certain scenario components are dependent on other components. Incident occurrence is the most prominent example: event properties (e.g., frequency, duration, and severity) tend to be affected by weather and other external events. Dependencies are also observed on the traffic management side: weather-responsive traffic management (WRTM) strategies are deployed based on type and severity of weather events, and traffic incident management is triggered by incident events. In the Scenario Manager, such dependencies are taken into account during the generation process. Once the scenario components of interest are defined, it identifies dependency relations between components and derives a generation order such that components that affect others are generated before their dependent ones. Following the generation order, the Scenario Manager

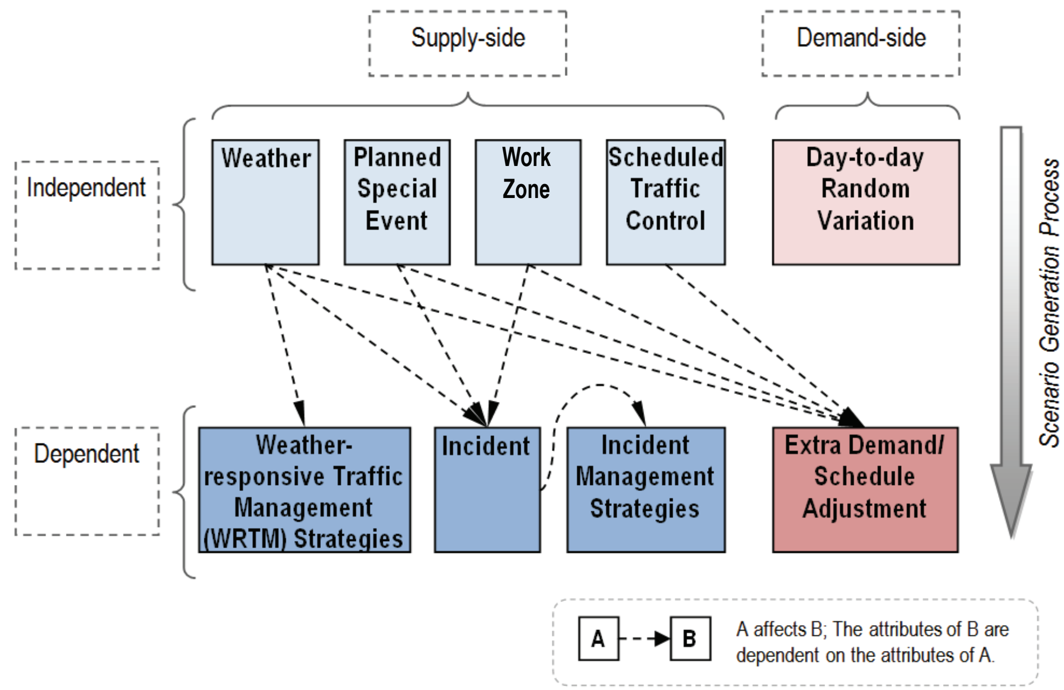
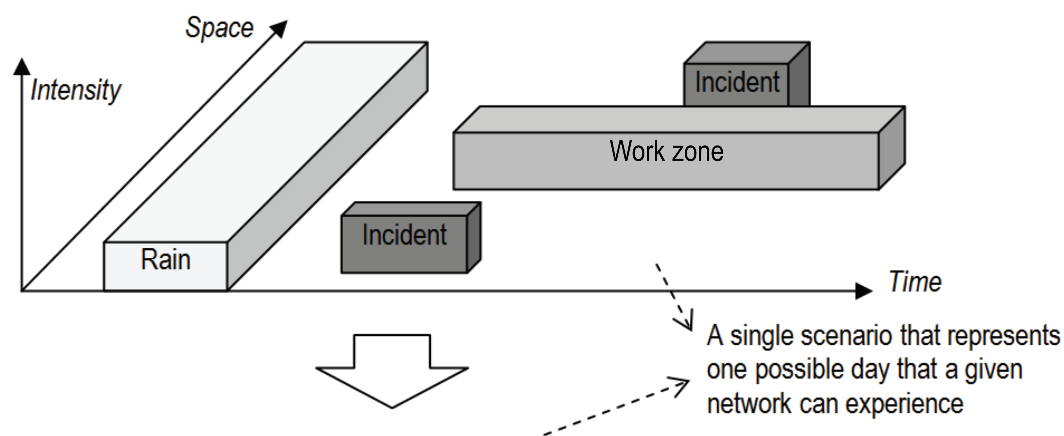


Figure 5.1. *Various scenario components and dependency relations.*



Event No.	Event Type	Start-Time	End-Time	Location (lat.,lon.)	Intensity
1	Weather	6:00 AM	7:00 AM	Network-wide	Light rain
2	Incident	8:05 AM	8:50 AM	Link A (40.xxx, -74.xxx)	2 lanes closed
3	Work zone	8:30 AM	3:00 PM	Link B (40.xxx, -74.xxx)	Road closure
4	Incident	9:45 AM	10:20 AM	Link C (40.xxx, -74.xxx)	1 lane closed
:	:	:	:	:	:

Figure 5.2. *Definition of* scenario*: Combination of various event instances represented by time, space, and intensity properties.*

generates each component sequentially (e.g., weather → incident → incident management) so that each component is sampled from its distribution conditioned on all the previously sampled components.

DESIGN OF SIMULATION EXPERIMENTS

Monte Carlo Approach

This approach uses Monte Carlo sampling to prepare input scenarios aimed at propagating uncertainties in selected scenario components (e.g., weather, incident, and demand variation) into uncertainties in the generated input scenarios. These uncertainties, in turn, can be translated into the resulting traffic simulation output (i.e., travel time distributions). The Scenario Manager performs Monte Carlo sampling to generate hundreds or thousands of input scenarios by drawing from the joint probability distribution of parameters for the selected scenario components. For instance, one could select weather and incidents as scenario components. In that case the Scenario Manager identifies the empirical distribution of weather events from historical weather data and estimates parameters for the stochastic process of incident occurrences based on incident data. Then it randomly samples a specified number of realizations of weather and incident combinations to construct input scenarios. Each scenario is equally likely, allowing the Trajectory Processor to simply aggregate travel time distributions from a large number of simulation runs to obtain the most likely (probable) estimators for a set of reliability performance indicators for the given time and space domains.

Mix-and-Match Approach

Instead of generating scenarios randomly given the underlying stochastic processes, one could explicitly specify scenarios with particular historical significance or policy interest. The mix-and-match approach aims to construct input scenarios in a more directed manner by mixing and matching possible combinations of specific input factors or by directly using known historical events or specific instances (e.g., holiday, ball game). Such design schemes are necessary when the user wants to control specific factors in constructing scenarios. For example, the user may set a demand pattern using actual data obtained from a particular ball game day while allowing other components such as weather, incident, and traffic controls to vary. The user can then identify all the possible scenarios under the ball game day by mixing and matching various scenario components, conditioning on the given demand pattern. By obtaining scenario-specific travel time distributions from each scenario's traffic simulation run as well as the probability of each scenario occurring, one can construct the overall travel time distribution and the associated reliability measures to assess travel time reliability on a ball game day.

OUTPUT ANALYSIS

Suppose that we simulated N input scenarios, S_i, $i = 1,\ldots, N$, and that we are interested in obtaining the overall distribution of travel time T that is the travel time for a given O-D/path/link under consideration. From the traffic simulation outputs, we obtain N

scenario-specific travel time distributions, denoted by conditional probability density function $f(T|S_i)$, $i = 1,\ldots, N$. Then the overall travel time distribution, the probability density function of T, $f(T)$ can be calculated by the weighted sum of the scenario-specific travel time distributions as follows:

$$f(T) = \sum_{i=1}^{N} f(T|S_i) P(S_i)$$

where $P(S_i)$ represents the probability of scenario S_i occurring $\left(\sum_{i=1}^{N} P(S_i) = 1 \right)$.

This process takes place within the Trajectory Processor, which accepts N vehicle trajectory data sets (from N scenarios) as input and processes the trajectory data to construct both scenario-specific and combined travel time distributions for any given trip. The graphical user interface (GUI) of the Trajectory Processor allows users to select the entire network, sub-area, specific O-D pair, path/segment, or link on the study network; it also provides various visualization options for displaying the associated travel time distributions and reliability measures listed in Table 2.1. Users can export all the data presented on the GUI of the Trajectory Processor to text files so that further analysis can be performed using spreadsheets or statistical tools.

The Trajectory Processor is designed to load multiple data sets from different scenarios so that users can compare reliability performance measures under different scenarios as well as obtain the combined travel time distribution aggregated over multiple scenarios with different scenario probabilities or weights.

Another important function provided by the Trajectory Processor is the ability to process GPS observations. The Trajectory Processor internally conducts a pre-processing step in which it maps GPS traces based on the real-world coordinate system to the link-node representation associated with the simulation network under consideration. This allows users to analyze GPS trajectories in the same manner as the simulated trajectories. Users can load the GPS trajectory data set, extract reliability measures for a given spatial boundary (e.g., entire network, sub-area, specific O-D pair, path/segment, or link), and compare the travel time distribution from the GPS data to that from the simulation result for validation purposes.

6 ASSESSING THE RESULTS

Assessing the results is briefly described from a system standpoint and also from a traveler standpoint in the following sections.

SYSTEM STANDPOINT

Transportation management agencies often need to measure reliability performance levels of given transportation systems: the entire network, sub-area, or specific corridor. The agencies can design and perform the simulation experiments to obtain the complete distribution of travel times the particular system could ever experience over different times of day and different days. The results (i.e., the overall travel time distribution and the associated reliability measures) can be used to answer questions like the following: How dispersed are travel times on this system? What proportion of travelers experience serious congestion along this road? How unreliable or uncertain is the travel time on a given road compared with another road?

ASSESSING TRAVEL TIME UNCERTAINTY DURING A PARTICULAR DEPARTURE TIME INTERVAL: TRAVELER STANDPOINT

Transportation management agencies also need to be able to estimate and predict the reliability levels that individual travelers will experience so they can provide travelers with accurate travel information or warning messages. Agencies can obtain the travel time distribution for a particular departure time interval to assess the probability that a particular traveler departing at that interval will experience a specific level of congestion. Another important user-level measure is the schedule delay experienced, which is the difference between the actual and the desired arrival time for that individual.

7 CASE STUDIES

To illustrate the process and the use of the tools, case studies for the microscopic and the mesoscopic models are provided in the following sections.

MICROSCOPIC MODELING CASE STUDY

Problem Statement

On a main arterial street in Manhattan, a certain section is known to experience significant delays as a result of incidents occurring during the a.m. peak period. One of the frequent incident locations is along Third Avenue between 53rd and 54th Streets. This roadway is a one-way, main arterial street that contains parking lanes on both sides. The city's transportation authorities wanted to investigate the impact on travel time reliability should the left-hand-side parking lane be converted to a live driving lane during peak periods.

Test Design

A microsimulation model of the East Side Manhattan network was used to provide some insights on this problem. The model network area is shown in Figure 7.1.

Two scenarios were tested and simulated trajectory outputs were obtained, from which the reliability measures were determined.

Scenario A can be regarded as the base scenario and is meant to represent the network operating under current conditions with the suggested improvement not yet in place. For Scenario A, an incident was introduced into the model at the location described in the problem statement, while the left-side parking lane was not yet converted to a driving lane. The incident was assumed to occupy the right driving lane, and its duration was 2 hours starting at 8:30 a.m.

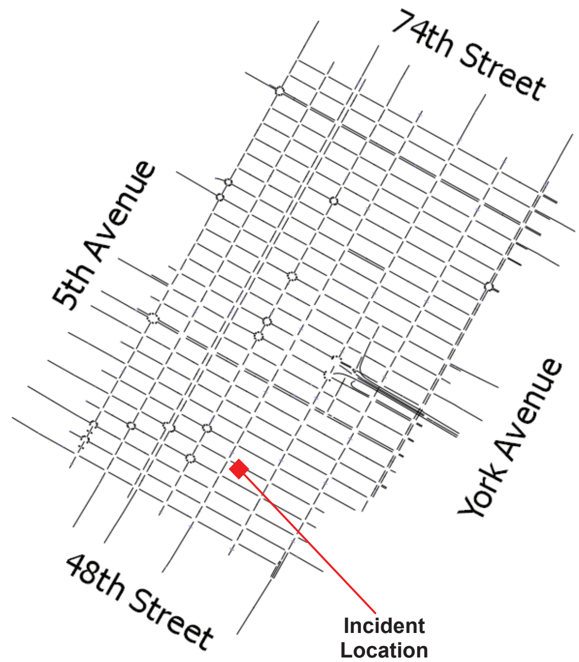


Figure 7.1. *Microsimulation model network.*

Scenario B modeled the improvement to the network, that is, conversion of the left-side parking lane to a driving lane between 52nd and 55th Streets. This condition was introduced for the entire simulation period of 5 hours, which started at 6:00 a.m. and ran until 11:00 a.m. The same incident was assumed to occupy the right driving lane between 53rd and 54th Streets for 2 hours starting at 8:30 a.m.

The trajectory outputs of the microsimulation model were input into the Trajectory Processor, and various travel time reliability metrics were produced.

Trajectory Processor Results

The results focus on the performance of the Third Avenue corridor where the improvement was implemented. For the purposes of this report, the results are provided for the three middle hours of the simulation when the traffic congestion and demand are at peak conditions as depicted in Figure 7.2.

Study Findings

The results show that, for the improved scenario, the added capacity improved the travel time reliability along the corridor. Both the average travel time and the average travel time standard deviation improved, as did the 95th percentile travel time.

The Buffer Index statistic (which is a representation of the variation of the trajectory travel times relative to the mean) through the corridor shows that, with the exception of the first hour, the travel time variability decreases in the improved scenario; that indicates an overall improvement in travel time reliability. The improved scenario

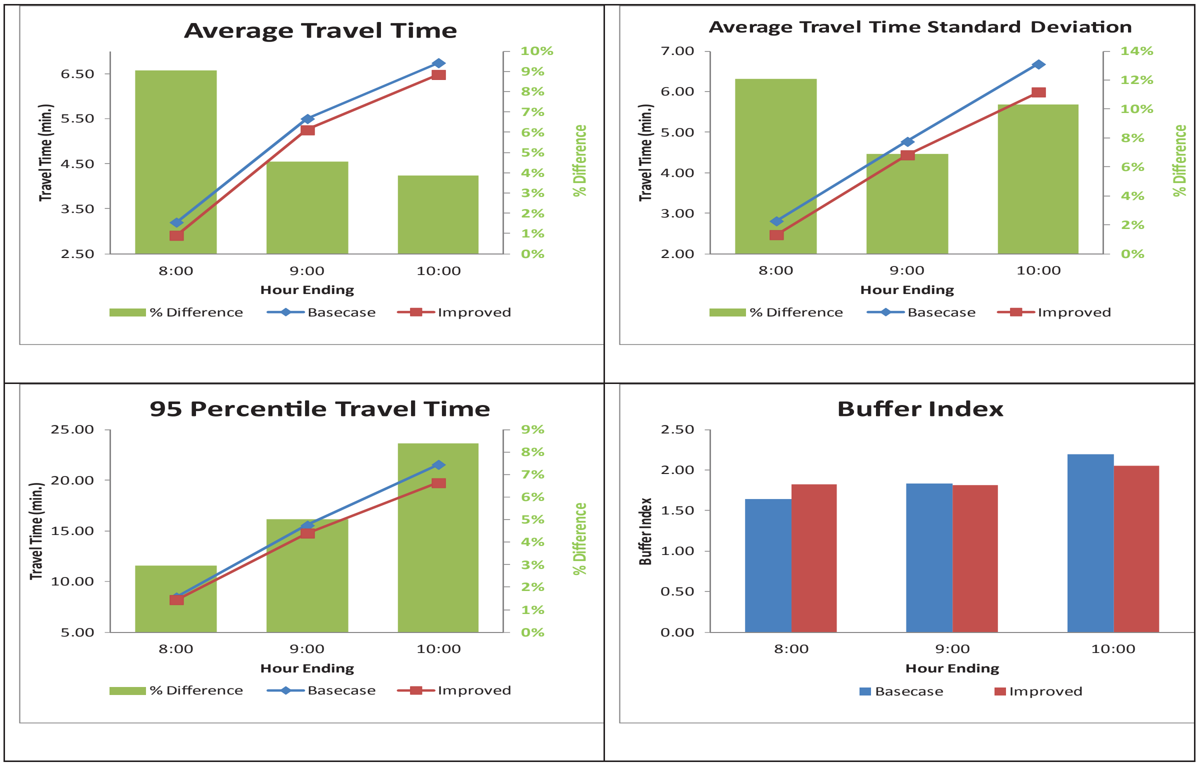


Figure 7.2. *Travel time reliability metrics.*

has a higher Buffer Index during the first hour because the 95th percentile travel time is similar for both scenarios, whereas the average travel time is almost 10% lower for the improved scenario compared with the base scenario. It is noteworthy that the average travel time standard deviation for the first hour is more than 10% lower for the improved scenario versus the base case. This means that the travel time reliability is generally better across all the time intervals for the improved scenario versus the base case.

MESOSCOPIC MODELING CASE STUDY

Problem Statement

This application examines the effect of different weather conditions on the travel time distributions throughout the New York City regional network for different days of the week. Specifically, the team obtained reliability performance measures for the following four scenario cases: weekdays under no rain, weekends under no rain, weekdays under rain, and weekends under rain. The purpose of this case study is to demonstrate the reliability analysis procedures in a mesoscopic traffic simulation model, in this case DYNASMART-P. The test network covers most of New York City and part of New Jersey, as depicted in Figure 7.3.

Figure 7.3. *New York City network for analysis using DYNASMART-P. (Points A and B delineate the path along which travel time distributions were examined in Manhattan.)*

Test Design

Step 1. Formulate study objectives. The objective is to examine the effect of weather on travel time reliability for weekday and weekend traffic.

Step 2. Define scenario cases. Four scenario cases are defined by weather and day of week: weekdays under no rain, weekends under no rain, weekdays under rain, and weekends under rain.

Step 3. Generate specific scenarios for analysis. Specific scenarios under each of the four cases may be obtained either by generating random scenarios using the Scenario Manager's Monte Carlo sampling capability or by using deterministic scenarios from the existing historical scenarios. This case study uses the former approach, in which a random representative scenario is selected using Monte Carlo sampling for each category. Input factors and the associated probability distributions used for the sampling include the empirical distribution of rain events (intensity, duration, and frequency), weather-conditional incident distributions, and day-to-day random demand variations for weekdays and weekends, separately. Parameters were estimated from the historical data collected from the study area between May 1, 2010, and May 15, 2010. The relative likelihood of each scenario is also calculated, as presented in Table 7.1.

TABLE 7.1. JOINT AND MARGINAL PROBABILITIES FOR SCENARIO CATEGORIES

Day of week	Weather		Sum
	No Rain	Rain	
Weekday	**0.400**	**0.265**	0.665
Weekend	**0.265**	**0.070**	0.335
Sum	0.665	0.335	1.000

Step 4. Simulate scenarios. The specific scenarios are simulated using DYNASMART-P, and the associated vehicle trajectory data are obtained as simulation output and supplied to the Trajectory Processor.

Step 5. Obtain reliability statistics using Trajectory Processor. Travel time distributions are constructed and various reliability performance measures extracted at the desired level of analysis (link, path, O-D, overall).

Trajectory Processor Results

The Trajectory Processor allows users to load vehicle trajectory data from multiple scenarios and investigate measures for both scenario-specific and combined travel time distributions. Figure 7.4 shows a dialog that displays a list of performance measures for each origin–destination (O-D) pair and its associated paths. Users can select a specific O-D pair from a map (Figure 7.5) or identify available paths for each O-D on the map by clicking rows in the Figure 7.4 table on the dialog; paths are depicted in Figure 7.6. Figure 7.7 shows a chart dialog that displays probability density functions, cumulative distribution functions (CDF), and time-dependent average travel times for different scenarios.

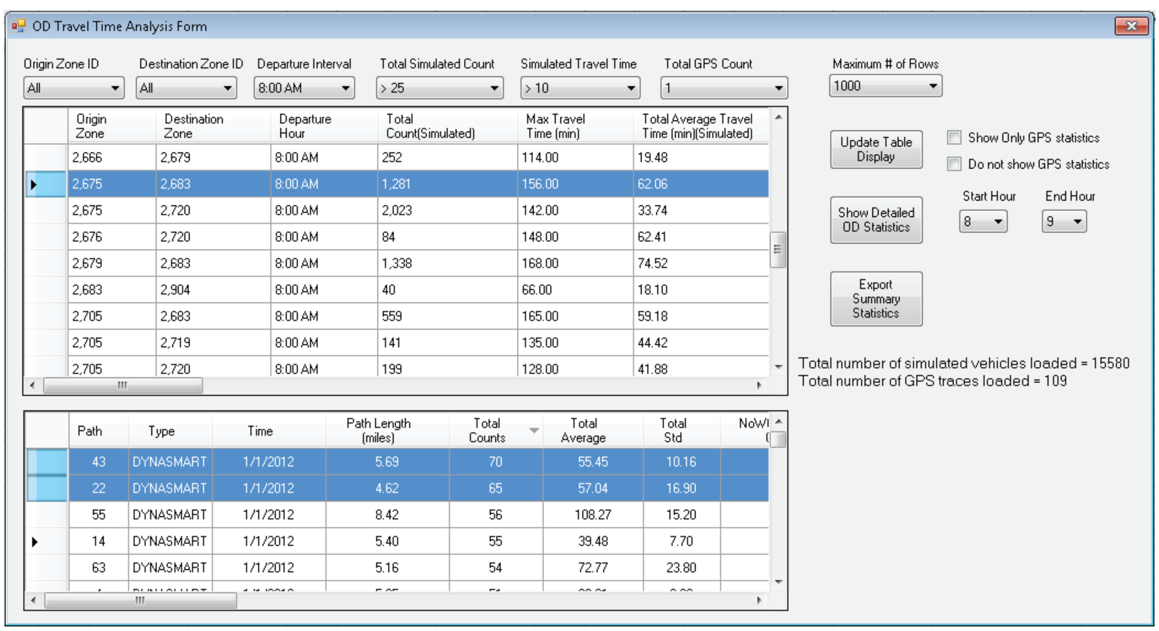


Figure 7.4. *Trajectory Processor GUI: List of available O-D pairs and paths.*

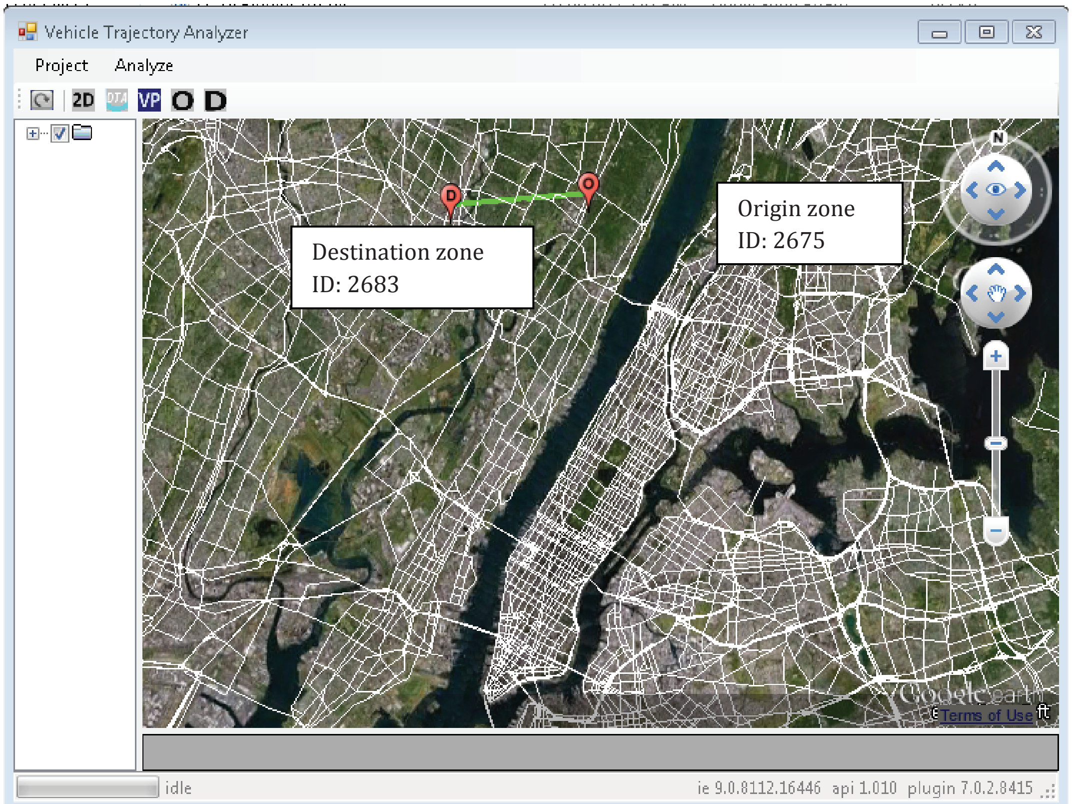


Figure 7.5. *Trajectory Processor GUI: Selected O-D pair displayed on map.*

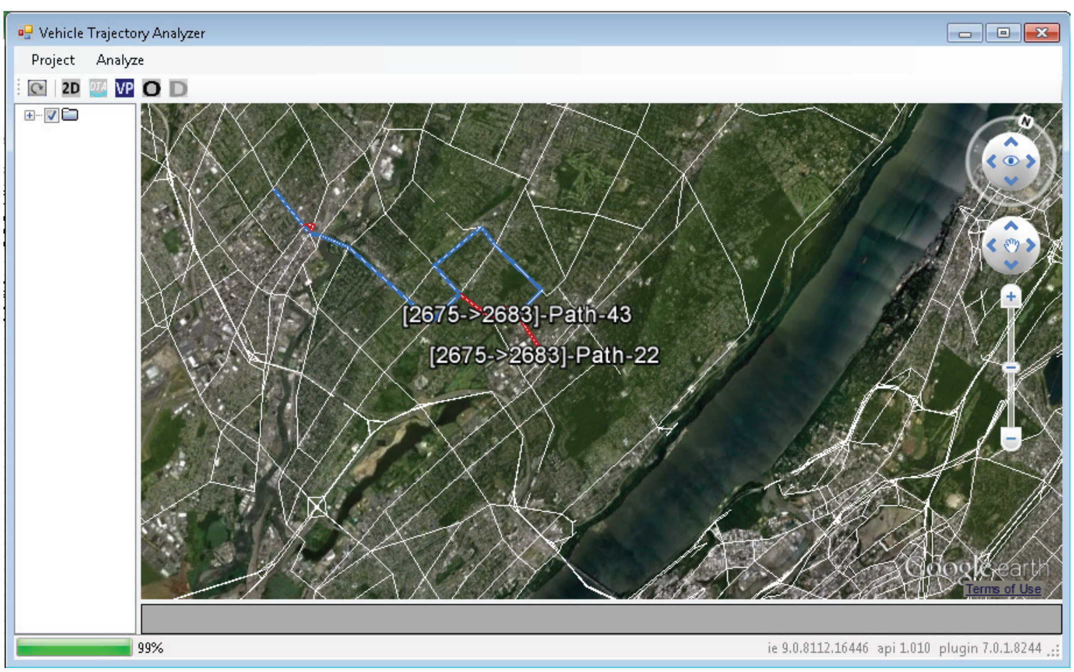


Figure 7.6. *Trajectory Processor GUI: Selected paths displayed on map.*

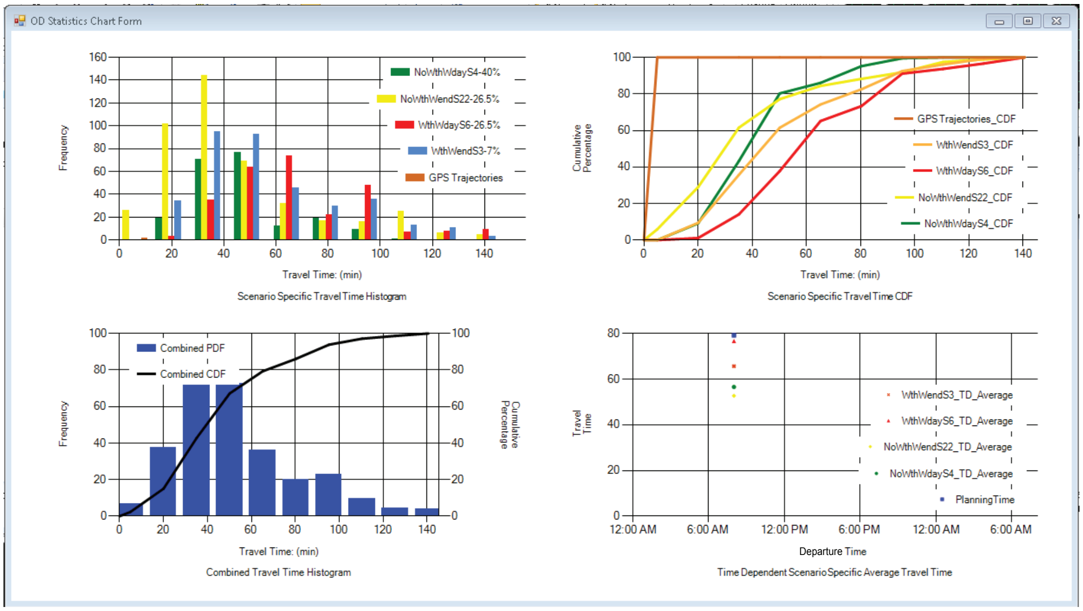


Figure 7.7. *Trajectory Processor GUI: Travel time distributions for selected O-D.*

Study Findings

As discussed in Chapter 2 (i.e., Table 2.1), different reliability metrics are used to assess the reliability performance at different levels of the system: network level, O-D level, and path level.

Network Level

For network-level analysis, distance-normalized measures are used. The 95th percentile travel time per mile is selected for this case study; time-dependent values for this measure for each scenario are presented in Figure 7.8. The networkwide extreme congestion level increases in the order of Weekend–No Rain, Weekday–No Rain, Weekend–Rain, and Weekday–Rain.

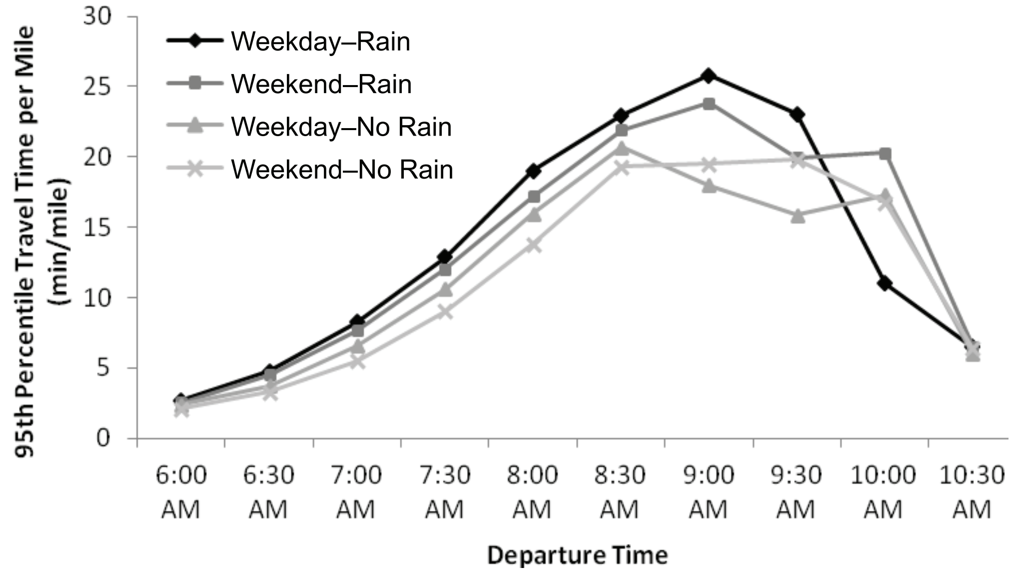


Figure 7.8. *Network-level measure: 95th percentile travel time per mile.*

O-D Level

The O-D–level analysis is based on the origin–destination zone identified in Figure 7.5 (IDs 2675 and 2683). Table 7.2 shows the mean, standard deviation, and coefficient of variation of the travel time distribution under each scenario for the selected O-D. The pattern observed for this O-D is similar to that obtained at the network level.

TABLE 7.2. O-D–LEVEL MEASURE: MEAN, STANDARD DEVIATION, AND COEFFICIENT OF VARIATION OF TRAVEL TIME DISTRIBUTIONS

Scenario Category	Number of Observations	Probability	Mean Travel Time (min)	Standard Deviation of Travel Times (min)	Coefficient of Variation
Weekday–Rain	270	0.265	76.7	26.6	0.35
Weekend–Rain	361	0.070	65.7	27.9	0.43
Weekday–No Rain	208	0.400	56.6	19.2	0.34
Weekend–No Rain	442	0.265	52.7	29.3	0.56
Combined	1281	1.000	62.1	28.4	0.46

Path Level

The team examined travel time distributions along a specific path between Points A and B, as shown in Figure 7.3. The Buffer Index is calculated using the definition given in Table 2.1. Figure 7.9 shows time-dependent Buffer Index values for each scenario. These indicate that the effect of weather is more pronounced than the day-of-week effect, as both weekday and weekend scenarios under rain exihibit noticeable increases in their Buffer Index values. Under the same rain condition, however, the day-of-week effect is also clearly observed. A peak in the Buffer Index takes place earlier (7:00 a.m. to 7:30 a.m.) for the weekday scenario than for the weekend scenario (8:00 a.m. to 8:30 a.m.).

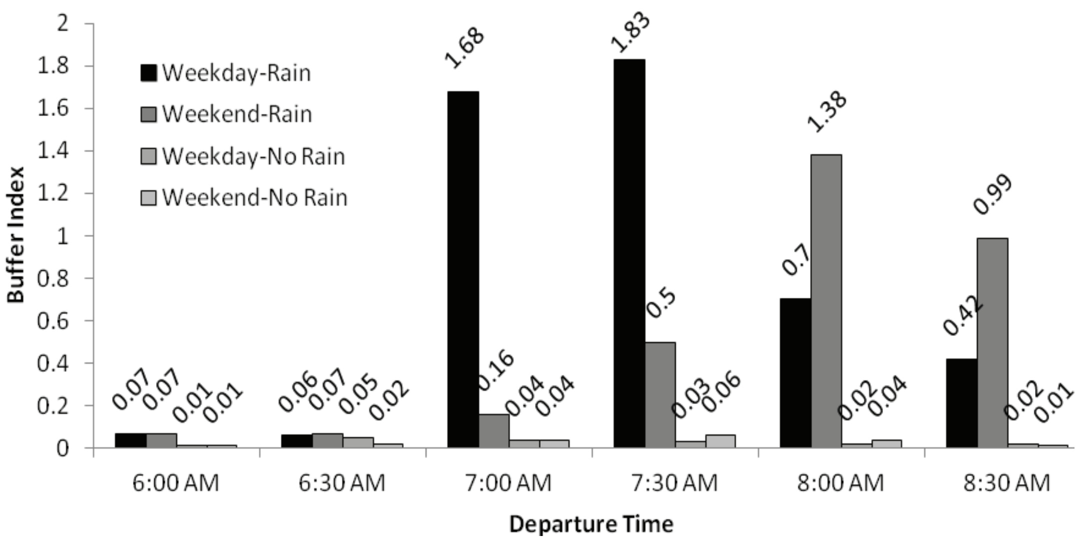


Figure 7.9. *Path-level measure: Time-dependent Buffer Index.*

8 TRAVEL TIME RELIABILITY IN PLANNING MODELS

The potential linking of travel demand forecasting models to traffic microsimulation provides the opportunity to more accurately represent traffic conditions, which can be fed back to choices about travel time, travel route, travel mode, or the decision to travel at all. This section highlights the importance of a feedback mechanism that could incorporate travel time reliability into traditional trip-based travel demand models, emerging activity-based models, and route choice models. The section summarizes the implemented synthesis of the research literature and testing of various methods to incorporate travel time reliability into operational travel models. Incorporation of reliability is primarily considered in the overall framework of demand-network equilibrium, with the demand side represented by an advanced activity-based model (ABM) and the network simulation side represented by an advanced dynamic traffic assignment (DTA). Whenever possible, the discussion is extended to incorporate traditional four-step demand models and static equilibrium assignment models.

FINDINGS AND RECOMMENDATIONS ON ABM-DTA INTEGRATION

Several aspects of ABM-DTA integration and associated feedback mechanisms are essential and need to be addressed even before incorporation of travel time reliability measures. New methods of equilibration of ABM and DTA include the following technical solutions to be applied in parallel:

- *Individual schedule consistency and temporal equilibrium*. Individual schedule consistency means that for each person, the daily schedule (i.e., a sequence of trips and activities) is formed without gaps or overlaps. This solution is based on the fact that a direct integration at the disaggregate level is possible along the temporal dimension if the other dimensions (number of trips, order of trips, and trip destinations) are fixed for each individual. The inner loop of temporal equilibrium includes schedule adjustments in individual daily activity patterns, made because congested travel times are different from planned travel times. The purpose of this feedback is to achieve consistency between generated activity schedules (activity start times, and times and durations) and trip trajectories (trip departure time, duration, and arrival time). The feedback is implemented as part of temporal equilibrium between ABM and DTA when all trip destinations and modes are fixed, but departure times are adjusted until a consistent schedule is built for each individual. In this way, any change in travel time would realistically affect activity durations and vice versa.

- *Presampling of trip destinations*. In the second solution, trip origins, destinations, and departure times are presampled. The DTA process then only needs to produce trajectories for a subset of origins, destinations, and departure times. In this case, the schedule consolidation is implemented through corrections to the departure and arrival times (based on the individually simulated travel times) and is employed as an inner loop. The outer loop includes a full regeneration of daily activity patterns and schedules but with a subsample of locations for which many individual trajectories are available. Destinations for which individual trajectories have not been generated at the previous iterations use conventional aggregate origin–destination skims.
- *Specific methods to ensure equilibration and convergence with individual microsimulation*. These methods include various enforcement and averaging strategies. Enforcement methods are specific to microsimulation and designed to ensure convergence of "crisp" individual choices by suppressing or avoiding Monte Carlo variability. Averaging methods have been borrowed from conventional four-step modeling techniques, but they can be also used with microsimulation as long as they are applied to continuous outputs/inputs such as level of service (LOS) variables and/or synthetic trip tables generated by the demand microsimulation process.
- *ABM improvements for better compatibility with DTA*. Several aspects of ABMs can be improved to provide better inputs to DTA. Such improvements can also avoid additional procedures that are currently applied to overcome structural incompatibilities that exist between the two models (e.g., randomly slicing trips by departure time). Three important aspects are (1) enhanced temporal resolution in trip departure choice, (2) car occupancy and associated conversion of person trips into auto trips, and (3) inclusion of route type choice as part of the mode choice tree.
- *Compatible user segmentation, preserving individual randomized value of time (VOT) and value of reliability (VOR)*. For full compatibility between the demand model and the network simulation model, the relevant individual parameters have to be transferred between the two. Network simulations, and specifically route choice, are not directly influenced by travel purpose or income or car ownership; these effects can instead be encapsulated in the VOT and VOR parameters. There are two principal ways to ensure the necessary compatibility between ABM and DTA: (1) preserve individual VOT and VOR transferred from ABM to DTA with the corresponding list of trips to simulate, and (2) form user classes with similar VOT and VOR to simplify path-building procedures that can be applied for each class.

FINDINGS AND RECOMMENDATIONS ON INCORPORATION OF RELIABILITY

The incorporation of reliability into a network simulation model requires innovative approaches to generate the reliability measures that are fed into the demand model, to make route choice sensitive to reliability measures, and to ensure that a realistic correlation pattern is taken into account when route-level measures of reliability are constructed from link-level measures.

The four main methods for quantifying reliability and its impacts are as follows:

- *Perceived highway time by congestion levels*. This concept is based on statistical evidence that travelers perceive each minute of travel time with a weight related to the level of congestion. Although segmented by congestion levels in this method, perceived highway time is not a direct measure of reliability, because only average travel time is considered. It can serve, however, as a good instrumental proxy for reliability, since the perceived weight of each minute spent in congestion is in part a consequence of associated unreliability.
- *Time variability distribution measures* (*or mean-variance approach*). This method has received considerable attention in recent years and is considered the most practical direct approach. It assumes that several independent measurements of travel time are known that allow for forming the travel time distribution and the calculation of derived measures such as buffer time. One important technical detail with respect to generation of travel time distributions is this: Even if the link-level time variations are known, synthesizing the O-D–level time distribution (reliability "skims") is a nontrivial task because of the dependence of travel times across adjacent links due to a mutual traffic flow.
- *Schedule delay cost*. According to this concept, the direct impact of travel time unreliability is measured through cost functions (penalties expressed in monetary terms) of being late (or early) compared with the planned schedule of the activity. This approach assumes that the desired schedule (preferred arrival time for each trip) is known for each person and activity in the course of the modeling. This assumption, however, is difficult to meet in a practical model setting.
- *Loss of activity participation utility*. This method can be thought of as a generalization of the schedule delay concept. It assumes that each activity has a certain temporal utility profile and that individuals plan their schedules to achieve maximum total utility over the modeled period (e.g., day), taking into account expected (average) travel times. Then, any deviation from the expected travel time due to unreliability can be associated with a loss of participation in the corresponding activity (or gain if travel time proved to be shorter). This approach was recently adopted in several research works on DTA formulation integrated with activity scheduling analysis. Similar to the schedule delay concept, however, this approach suffers from data requirements that are difficult to meet in practice. The added complexity of estimation and calibration of all temporal utility profiles for all possible activities and person types is also significant. These concerns make it unrealistic to adopt this approach as the main concept for the current project.

The main features of the four approaches and associated features that have to be added to the demand model and network simulation model are summarized in Table 8.1.

TABLE 8.1. SUMMARY OF METHODS FOR INCORPORATING RELIABILITY INTO TRAVEL MODELS

Method	Demand Model	Network Simulation
Perceived highway time	Segmentation of highway time by congestion levels with differential weights; no significant modification of model structure required	Segmentation of highway time skims by congestion levels; no significant modification of model structure required
Mean-variance (time distribution measures)	Add variance or standard deviation as LOS variable along with mean travel time and cost to mode choice and other travel choices	Add variance or standard deviation to route generalized cost along with mean travel time and cost; employ path-based assignment and/or multiple-run framework; generate route variance or standard deviation skims for demand model
Schedule delay cost	Specify preferred arrival time (PAT) for each trip exogenously or generate PAT endogenously in time-of-day choice; calculate schedule delay cost based on PAT and travel time distribution	Incorporate schedule delay cost into joint route and departure time choice; generate O-D travel time distributions in single-run or multiple-run frameworks
Temporal activity profiles for participation in activity	Calculate generalized cost, including loss in activity participation based on travel time distribution	Incorporate temporal activity profiles into joint route and departure time choice; generate O-D travel time distributions in single-run or multiple-run frameworks

FINDINGS AND RECOMMENDATIONS ON IMPLEMENTATION FRAMEWORK

The corresponding technical solutions are broken into two groups: single-run framework and multiple-run framework. Incorporation of reliability factors into the models can be done in either of two principal ways:

- *Implicitly in a single model run*, in which travel time is implicitly treated as a random variable and its distribution, or some parameters of this distribution (such as mean and variance), are described analytically and used in the modeling process.
- *Explicitly through multiple runs (scenarios)*, in which the travel time distribution is not parameterized analytically but is simulated directly or explicitly through multiple model runs with different input variables. The Scenario Manager is an essential tool to make the multiple-run approach operational.

There are pros and cons associated with each method. The vision emerging from this research is that both methods are useful, and each could be hybridized to account for different sources of travel time variation in the most adequate and computationally efficient way. Whenever possible, single-run analytical methods are considered; they are generally preferable from a theoretical point of view, particularly for network equilibrium formulations, and in terms of a more efficient use of computational resources in application. Generally, the factors that can be described by means of analytical tools and probabilistic distributions relate to the baseline demand and capacity estimates, day-to-day variability in travel demand, impact of weather conditions, traffic control, route choice, mesoscopic effects associated with traffic flow physics, and individual driver behavior. Factors that can be better modeled through explicit scenarios, rather than captured by probabilistic distributions, mostly relate to special events, road works, and occurrence of incidents. Some factors (like day-to-day fluctuations in demand, weather conditions, and traffic control) can be modeled both ways.

9 NEXT STEPS FOR APPLICATION

This project has developed and demonstrated a unified approach with broad applicability to various planning and operations analysis problems, which allows agencies to incorporate reliability as an essential evaluation criterion. The approach is independent of specific analysis software tools, in order to enable and promote wide adoption by agencies and developers. The project has also developed specific software tools intended to prototype the key concepts—namely, Scenario Manager and Trajectory Processor—and demonstrated them with two commonly used network modeling software platforms.

AGENCY ADOPTION

Throughout this study, it has become clear that reliability as an evaluation and decision factor is here to stay. It is therefore essential for agencies and the consultants who support them to provide the inputs required to consider reliability when designing and evaluating future programs, projects, and policies. Agency hesitation to adopt new approaches is rooted in two factors: (1) the institutional cost of doing something different and (2) lack of trust and experience in the new generation of tools available to address this need. The present project provides the approaches and tools to address the second factor. Furthermore, it addresses the first factor by developing an approach that is essentially software neutral and can be readily adapted with the agencies' existing modeling tools.

Nonetheless, unless developers of commercial software can provide the necessary utilities and linkages to fully enable reliability-based analysis approaches, agencies will not totally come on board. The SHRP 2 program has taken important steps to create further awareness of the importance of reliability as a decision factor and of the availability of these new approaches and tools.

To further promote agency adoption, it is important to identify and facilitate early adopters. Early adopters are those agencies that will show the way and that other agencies can point to as successful examples to be emulated. Program funding for demonstration projects with full agency engagement and commitment is therefore an essential ingredient to achieving greater agency adoption.

DEVELOPERS

Developers of commercial software application tools for both planning and operations applications play a critical role in the dissemination of new knowledge and advances in methodology developed under projects such as this one. The project team members are themselves actively engaged in the application and further development of the tools and their application; however, the transportation field is a vast one that requires a large number of players to work toward similar technical goals.

The approaches and tools developed in this project are readily applicable with most software tools for microscopic and mesoscopic network simulation, albeit to varying degrees of completeness. The steps required by developers are relatively minor given the templates and code developed for this project. Naturally, commercial developers would all like to somehow add unique value to their offerings, for competitive market reasons. However, they will only do so if they believe there is market demand for the capability. This is how a few early agency adopters will start the cycle of agency demand and developer supply. The present project has removed the technical risk for the developers, who need only invest in programming time to customize to their software's unique features.

SUCCESS FACTORS

Key success factors for the results of this project include the following:

- Create greater awareness of the importance of reliability analysis for major planning and operations projects, as well as of the attainability of such analysis capabilities.
- Adopt scenario-based approaches to project evaluation as the primary, default approach for conducting such evaluations.
- Promote greater appreciation and recognition of the entire distribution of travel time, rather than simply mean values.
- Make utilities available for use in connection with most network simulation software both to manage the creation and generation of scenarios and to analyze the output of such scenario runs to obtain travel time distributions and reliability descriptors.

RECOMMENDATIONS FOR FUTURE RESEARCH

Several important research directions have become clear in the course of the current project. Many of them relate to more advanced methods of incorporating travel time reliability, specifically schedule delay cost, and temporal activity profiles. However, improving travel demand models and network simulation tools in this direction is closely intertwined with the general improvement of individual microsimulation models. The following specific recommendations for future research are made:

- Continue research on advanced methods for incorporating travel time reliability into demand models and network simulations tools, including the schedule delay cost approach and temporal utility profile (loss of activity participation) approach. In this regard, continue research and development of path-based assignment algorithms that incorporate travel time reliability and can generate a trip travel time distribution in addition to mean travel time.
- Continue research on schemes for the integration of advanced ABM and DTA that can ensure a full consistency of daily activity patterns and schedules at the individual level and behavioral realism of traveler responses. In this regard, addressing enhancement of time-of-day choice, trip departure time choice, and activity scheduling components is essential. This point relates to the conceptual structure of these models and their implementation with respect to temporal resolution.
- Encourage additional data collection on the supply side of activities and on scheduling constraints—including the distribution of jobs and workers by schedule flexibility and classification of maintenance and discretionary activities by schedule flexibility—and develop approaches to forecast related trends.
- Continue research on and application of multiple-run model approaches and associated scenario formations, for both the demand and network supply sides. The synthesis and research from this project have shown that a conventional single-run framework is inherently too limited to incorporate some important reliability-related phenomena such as nonrecurrent congestion due to a traffic incident, special event, or extreme weather condition.
- Incorporate travel time reliability in project evaluations and user benefit calculations. Restructure the output of travel models to support project evaluation and user benefit calculations with consideration of the impact of improved travel time reliability.

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