Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes: Technical Reference

DETAILS

185 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-27319-0 | DOI 10.17226/22594

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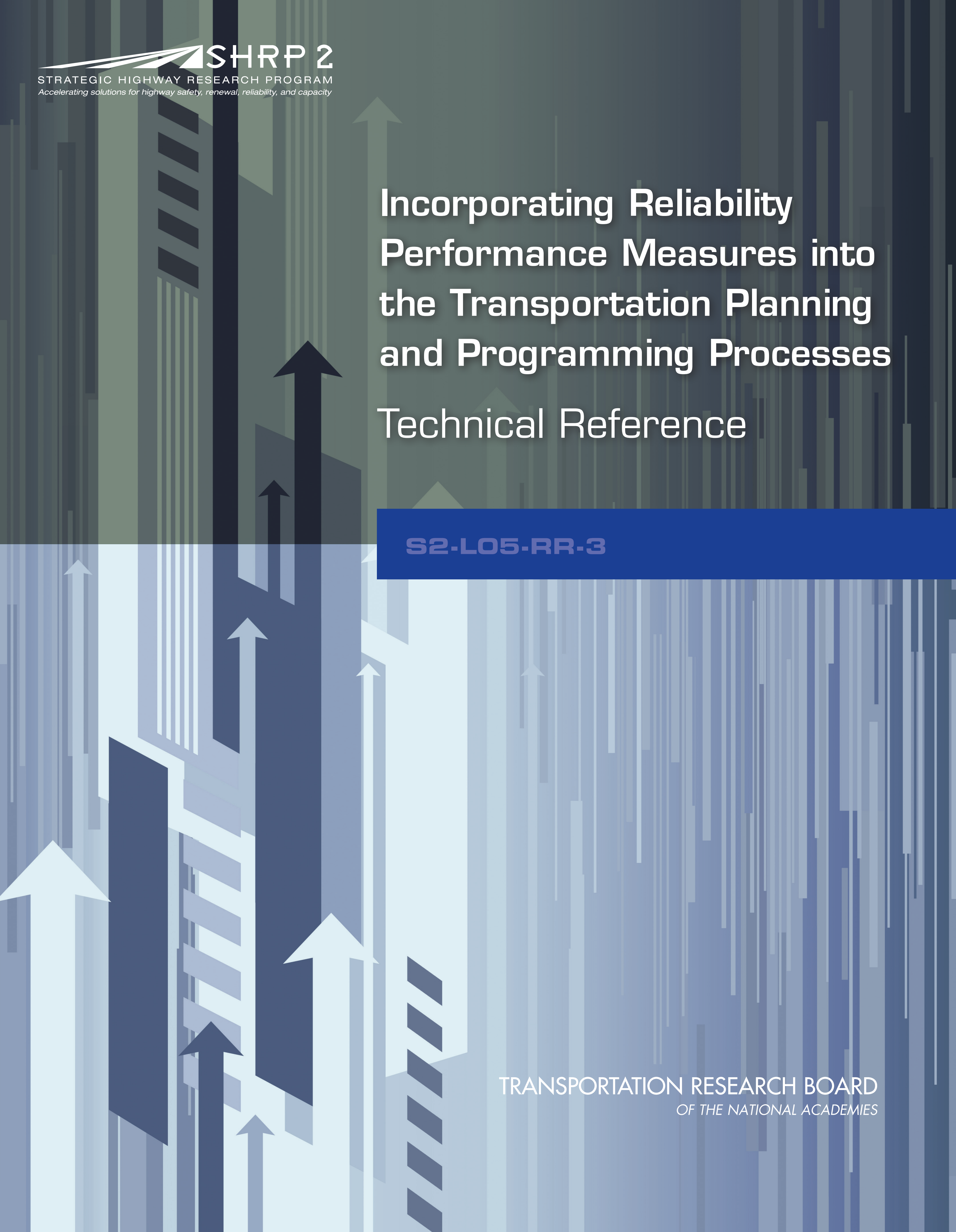

SHRP 2
STRATEGIC HIGHWAY RESEARCH PROGRAM
Accelerating solutions for highway safety, renewal, reliability, and capacity

Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes

Technical Reference

S2-L05-RR-3

TRANSPORTATION RESEARCH BOARD
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THE SECOND STRATEGIC HIGHWAY RESEARCH PROGRAM

Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes: Technical Reference

SHRP 2 Report S2-L05-RR-3

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TRANSPORTATION RESEARCH BOARD

Washington, D.C.
2014
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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.

SHRP 2 Report S2-L05-RR-3
ISBN: 978-0-309-27319-0
Library of Congress Control Number: 2014946506

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The project that is the subject of this report was a part of the second Strategic Highway Research Program, conducted by the Transportation Research Board with the approval of the Governing Board of the National Research Council.

The members of the technical committee selected to monitor this project and to review this report were chosen for their special competencies and with regard for appropriate balance. The report was reviewed by the technical committee and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the Governing Board of the National Research Council.

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ACKNOWLEDGMENTS

This work was sponsored by the Federal Highway Administration in cooperation with the American Association of State Highway and Transportation Officials. It was conducted in the second Strategic Highway Research Program (SHRP 2), which is administered by the Transportation Research Board of the National Academies. The project was managed by William Hyman, Senior Program Officer for SHRP 2 Reliability.

The authors would like to acknowledge the many useful contributions of the project panel. The authors would also like to acknowledge the contributions of staff at several transportation agencies that supported the research by providing data and information for several case studies, including the Knoxville Metropolitan Planning Organization, the Florida Department of Transportation, the Washington State Department of Transportation, the Los Angeles Metropolitan Transit Authority, the Southeast Michigan Council of Governments, the Colorado Department of Transportation, and the Denver Regional Council of Governments.

Cambridge Systematics, Inc., supported by Texas A&M Transportation Institute, Sharp & Company, Inc., PB Americas, and Arun Chatterjee, performed the research reported.

FOREWORD

William Hyman
Senior Program Officer for SHRP 2 Reliability

Virtually all transportation agencies today have a strong customer orientation. An important concern of road users is congestion that is both recurring and nonrecurring. Recurring congestion is periodic in nature, such as rush hour or holiday travel. Nonrecurring congestion is unexpected and is due to crashes, weather, unfamiliar work zones, special events, failure of traffic control devices, surges in demand, and the interaction of inadequate base capacity with these factors. All these sources of congestion affect travel time reliability. Just in the past decade or two, agencies have begun to collect data and measure reliability; in other words, they are measuring how travel time varies over time. A critical question is how agencies should use their limited funds to achieve more cost-effective outcomes, such as improved congestion, and consequently reduce delay and less-reliable travel times. A related, critical question is, can greater collaboration both within and outside their agencies result in better programs and projects that achieve agency objectives, including improving travel time reliability?

With the enactment of Moving Ahead for Progress in the 21st Century (MAP-21), state and metropolitan transportation agencies must adopt performance-based planning and programming that embraces measures and targets for travel time reliability along with safety, infrastructure condition, congestion reduction, sustainability, freight movement and economic vitality, and reduced project delivery delays. Performance-based planning and programming is expected to strengthen how to address future highway and other transportation needs, obtain better results, provide a feedback mechanism for assessing progress, and provide a framework for undertaking expenditure decisions, including, in particular, steering resources toward improving an agency’s performance.

Over many decades transportation decision making has become increasingly challenging and complex for reasons ranging from technological change to growing environmental concerns. Erosion in gas tax revenues has exacerbated the problem. Many transportation agencies continue to emphasize major highway construction, either new construction or large reconstruction projects. Other transportation agencies give the highest priority to maintaining the transportation system they now have, both its physical condition and operational functionality.

Whatever their posture and priorities, transportation agencies will need to carry out their work within the context of MAP-21. To do this will often require revised policy, more foresight, organizational change, and a willingness to determine the best use of money, to the extent that laws and regulations allow, across stovepipes as opposed to sticking with customary divisions of resources. Also, agencies will need a process for allocating their limited funds across the huge number of competing demands on the transportation network.

It will be imperative to identify and illuminate for all key stakeholders trade-offs among the key goal areas, including those of MAP-21, as well as to account for benefits that should be monetized. The categories of benefits that have been monetized and compared to costs have historically consisted of avoidable accidents, avoidable vehicle operating costs, avoidable travel time, and sometimes avoidable emissions.

As a result of research from many parts of the world, including SHRP 2 in the United States, it appears that drivers on many types of trips value improvements equal to a substantial fraction of improvements in average travel time. It is likely that improvements in travel time reliability will increasingly be included among the benefits expressed in terms of money. While the benefits of all types of improvements, including major projects, will increase, overall operational improvements will be more cost-effective.

SHRP 2 Reliability Project L05, Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes, has resulted in a report, a guide, a technical reference, case studies, and some simple spreadsheets. The report reviews domestic and international literature describing current research and state of the practice in using travel time reliability in transportation planning; summarizes case studies from agencies working to incorporate reliability into their transportation planning processes; summarizes travel time reliability performance measures, strategies for improving travel time reliability, and tools available for measuring the impacts strategies have on travel time reliability; and describes the framework for incorporating reliability performance into transportation planning processes.

The guide is an easy-to-read explanation aimed at managers and others regarding how to incorporate travel time reliability into planning and programming through a collaborative process. The guide introduces the concept of travel time reliability, identifies various reliability measures, explains how to incorporate reliability into policy statements, describes how to evaluate reliability needs and deficiencies, and, finally, offers suggestions on how to incorporate reliability measures into program and project investment decisions.

This technical reference amplifies the information in the guide and is aimed at analysts. Highlights include tools and methods for estimating reliability suitable for planning, steps for conducting a reliability analysis, incorporating reliability into benefit–cost analysis, and improving an agency's planning and programming capability.

If an agency can climb the ladder to higher levels of organizational capability and maturity, operations is then likely to be treated in an even-handed manner alongside construction, maintenance, safety, and other modes.

A third document available as a part of the L05 research consists of a series of case studies. Generally, the case studies were intended to expose a slice of the process for incorporating reliability into planning and programming. Together, the case studies help paint a picture of much of the entire process and serve to validate portions of the material in the guide and the technical reference.

The researchers prepared a number of relatively simple spreadsheets for several of the case studies. These spreadsheets are instructive regarding how to incorporate reliability in sketch-planning methods.

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1

INTRODUCTION

SHRP 2 Reliabililty Project L05, Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes, provides guidance for transportation planning agencies to help them incorporate travel time reliability performance measures and strategies into the transportation planning and programming process. This will allow operational improvements to be considered alongside more traditional types of capital improvements and ensure that transportation funds are being used as effectively as possible.

This document is the technical reference for incorporating reliability performance measures into the planning and programming process. It provides a how-to guide for technical staff to select and calculate the appropriate performance measures to support the development of key planning products, including the following:

- Long-range transportation plans;
- Transportation programs [State Transportation Improvement Programs (STIPs) and Transportation Improvement Programs (TIPs)];
- Congestion management process;
- Corridor planning; and
- Operations planning.

This technical reference is designed to accompany the guide written for planning, programming, and operations managers and focuses on the options that need to be considered to integrate reliability into the planning and programming process.

Detailed case studies were also developed as part of the L05 project to develop and validate the guidance and techniques presented in the guide and the technical reference. Reference to the case studies occurs throughout the technical reference. Table 1.1 summarizes the case studies referenced and used in the development of the technical

TABLE 1.1. KEY FINDINGS AND LESSONS FROM VALIDATION CASE STUDIES

Case Study	Objectives	Key Findings and Lessons	Possible References
Colorado DOT	Conduct a before and after analysis and benefits study of a pilot traffic operations project being conducted by Colorado DOT in Denver. One of the key themes of SHRP 2 L05 and other efforts is an attempt to mainstream operations planning within the broader planning process. This validation case study identifies methods to better achieve that objective.	Documents the process for conducting an arterial before and after analysis with emphasis on travel time reliability. Benefits of operations strategies in improving travel time reliability. Steps to incorporating reliability performance measures into the LRTP at CDOT. The findings validate the operations planning phase of the planning process.	Guide: Chapter 3 Technical Reference: Chapter 2 and Appendix D Guide: Chapter 6 Technical Reference: Chapter 6, Appendix B, and Appendix C Guide: Chapter 2 Technical Reference: N/A
Florida DOT	Document FDOT's efforts to incorporate travel time reliability into its planning and programming process, including incorporating reliability into its short range decision support tool (Strategic Investment Tool) and modeling techniques for predicting the impact of projects on reliability.	Incorporating reliability into the programming process is a challenge because of lack of specific funding categories and challenges due to statutory requirements regarding the types of projects that can be funded. The case study documented many success factors for incorporating reliability into the planning and programming process. The findings validate the programming phase of the planning process.	Guide: Chapters 2, 5, and 6 Technical Reference: Chapters 2 and 3
Knoxville, TN MPO	Demonstrate how reliability can be incorporated into the ITS/operations element of the region's upcoming LRTP and assist MPO staff in incorporating reliability performance measures in plan development, project identification, and project prioritization processes.	Developed a reliability objective for inclusion in the Congestion Management Process; Calculated reliability performance measures along freeways and incident-prone locations; Developed a method for incorporating reliability into the project selection process. The findings validate tools for quantifying travel time reliability using somewhat less sophisticated modeling and other tools.	Guide: Chapter 6 Technical Reference: N/A Guide: Chapter 3 Technical Reference: Chapter 5 and Appendix D Guide: Chapter 6 Technical Reference: Chapters 3 and 5
LAMTA (Los Angeles Metropolitan Transit Authority)	Document the development of an arterial performance monitoring system, which will be used to prioritize arterial operations projects for funding.	Recommends approach for using alternative data sources to support an arterial performance monitoring system. Preliminary findings suggest that multimodal reliability measures can be calculated from alternative data sources, although data source consistency is critical.	Guide: Chapters 3 and 4 Technical Reference: Chapter 2 and Appendix D

(continued)

TABLE 1.1. KEY FINDINGS AND LESSONS FROM VALIDATION CASE STUDIES (continued)

Case Study	Objectives	Key Findings and Lessons	Possible References
NCTCOG (North Central Texas Council of Governments—Dallas-Fort Worth)	Identify best practices on how other MPOs are incorporating reliability into their Congestion Management Process and provide recommendations on how NCTCOG can incorporate reliability into their planning process.	Only a limited number of MPOs have incorporated reliability into their CMP. Success factors include having robust amounts and sources of traffic data, using corridor-level measures and effective reporting graphics, defining reliability in a way that can be easily understood by multiple audiences, and having a performance measurement working group consisting of agency staff, technical/policy board members, local stakeholders, and the public.	Guide: Chapters 2, 4, and 6 Technical Reference: Chapters 2 and 5 and Appendix D
SEMCOG (Southeast Michigan Council of Governments—Detroit)	Identify reliability performance measures for assessing highway operations and develop a method for incorporating reliability into SEMCOG's performance-based program trade-off process.	Reliability can be incorporated in the trade-off analysis process and will likely affect the results of the prioritization process; the use of representative corridors can be effective in conducting a regional analysis; assessments of reliability can be conducted even in situations with limited data availability. The findings validate incorporation of reliability into a program-level trade-off analysis.	Guide: Chapters 5 and 6 Technical Reference: Chapters 5 and 6 and Appendix C
Washington State DOT	Incorporate reliability into identifying deficiencies and investments in a corridor	Establishes a methodology for examining reliability deficiencies for WSDOT corridor studies.	Guide: Chapters 3, 4, and 6 Technical Reference: Chapter 3

reference. SHRP 2's *Case Studies in Using Reliability Performance Measures in Transportation Planning* describes the detailed findings from each of the case studies.

A final report summarizes the research that was conducted as part of this project. It includes a summary of a literature review, a state of the practice survey, and validation case studies conducted to test the concepts and methods evaluated as part of this project. It also provides a detailed appendix that describes the linkage between this project and PlanWorks (formerly known as Transportation for Communities—Advancing Projects through Partnership or TCAPP), the keystone project of the SHRP 2 Capacity program.

SHRP 2 L05 draws from the research and techniques developed by many other SHRP projects. These are referenced throughout the technical reference. A table summarizing the studies and their relationship to L05 is shown in Appendix A, Table A.2.

This document is organized as follows.

- *Chapter 2: Overview of Travel Time Reliability*. This chapter, based on previous work in the SHRP 2 Reliability program, summarizes foundational research on reliability, including a practical definition, how to measure reliability, why reliability is important, and strategies for improving reliability.

- *Chapter 3: Description of Tools and Methods for Estimating Reliability*. This chapter summarizes the types of tools and methods that may be used to estimate reliability measures, including sketch planning, model post-processing, simulation or multiresolution, and monitoring and management.
- *Chapter 4: Tool and Method Selection Process*. This chapter provides processes for selecting a reliability analysis tool or method and guidance for setting up the analysis.
- *Chapter 5: Conducting a Reliability Analysis*. This chapter provides systematic guidance in applying reliability analysis methods and tools.
- *Chapter 6: Benefit–Cost Analysis*. This chapter provides guidance on incorporating the results of the reliability analysis into a benefit–cost analysis.
- *Chapter 7: Improving Planning and Programming Capability*. This chapter describes a Capability Maturity Model (CMM) approach for incorporating travel time reliability into planning and programming.

Select relevant material from outside sources is provided in supplemental appendices.

- *Appendix A: Additional Resources*. This appendix provides annotated descriptions of references and other resources where the user may obtain additional relevant information, including descriptions of other parallel ongoing efforts related to performance measurement, analysis tools and the planning process. It also includes a table summarizing all other SHRP projects referenced in this technical reference and in the guide.
- *Appendix B: Trends in Reliability*. This appendix presents an excerpt from the SHRP 2 L03 report, *Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies*, which provides an illustrative example of the challenges in interpreting the varied results of a reliability analysis.
- *Appendix C: IDAS Travel Time Reliability Rates*. This appendix presents the lookup tables from the ITS Deployment Analysis System (IDAS) tool that are required for some of the analysis methods.
- *Appendix D: Benefits and Costs of Full Operations and ITS Deployment—Technical Appendix*. This appendix presents additional information on completing a multiscenario post-processing method.
- *Appendix E: Data Collection Methods*. This appendix presents an overview of various types of traffic data and describes technologies and methods for collecting the data.
- *Appendix F: U.S. DOT Guidance on Performance Measures*. This appendix presents guidance on how to calculate various reliability measures from simulation model outputs.
- *Appendix G: Guidance to Improve TSM&O Planning and Programming Capability***.** This appendix presents guidance on the types of actions needed to improve an agency's capability in the seven critical dimensions of Transportation Systems Management and Operations (TSM&O) planning and programming.

2

OVERVIEW OF TRAVEL TIME RELIABILITY

Travel time reliability is a significant aspect of transportation system performance. Reliability is important to travelers and transportation practitioners for a variety of reasons.

- From an economic perspective, reliability is highly important because travelers must either build extra time in to their trips to avoid arriving late or suffer the consequences of being late. This extra time has value beyond the average travel time used in traditional economic analyses.
- Because of the extra time required in planning trips—and the uncertainty about what travel times will actually be for a trip—reliability influences decisions about where, when, and how travel is made.
- Because of the extra economic cost of unreliable travel on users, transportation planners and operators need to include these costs in the project planning, programming, and selection processes. This is particularly true of strategies that deal directly with roadway events (e.g., incidents). In the past, most assessments of these types of strategies have missed this important aspect of the travel experience.

2.1 HOW IS RELIABILITY DEFINED?

A review of several SHRP 2 projects—some completed, some still under way—was conducted to identify how they defined reliability.

Color versions of the figures in this chapter are available online:
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- Project C04 (Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand) defined reliability as “the level of (un)certainty with respect to the travel time and congestion levels.” It then used statistical measures, primarily the standard deviation of travel time, as the metrics used in subsequent analyses.
- Project C05 (Understanding the Contribution of Operations, Technology, and Design to Meeting Highway Capacity Needs) stated, “The reliability of the performance is represented by the variability that occurs across multiple days.”
- Project L01 (Integrating Business Processes to Improve Reliability) defined reliability as the “consistency of travel times for a particular trip. Travelers tend to estimate how long a trip will take based on parameters such as distance, time of day, and their own experience. Impacts to the transportation network that cause unexpected delays introduce uncertainty in travel time reliability.”
- Project L02 (Establishing Monitoring Programs for Mobility and Travel Time Reliability) used this definition: “It is important to start by observing that travel time reliability is not the same as (average) travel time . . . travel time reliability is about travel time probability density functions (TT-PDFs) that allow agencies to portray the variation in travel time that exists between two locations (point-to-point, P2P) or areas (area-to-area, A2A) at a given point in time or across some time interval. It is about estimating and reporting measures like the 10th, 50th, and 95th percentile travel times.” Functionally, Project L02 used the notion developed in Project L03 that reliability can be measured using the distribution of travel times for a facility or a trip.
- Project L03 (Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies) used an expanded definition of reliability to include not only the idea of variability, but failure (or its opposite, on time) as well. Quoting the Future Strategic Highway Research Program, the SHRP 2 L03 report stated, “From a practical standpoint, *travel time reliability can be defined in terms of how travel times vary over time* (e.g., hour-to-hour, day-to-day). This concept of variability can be extended to any other travel time–based metrics such as average speeds and delay. For the purpose of this study, travel time variability and reliability are used interchangeably.”(*1*)

A slightly different view of reliability is based on the notion of a probability or the occurrence of failure often used to characterize industrial processes. With this view, it is necessary to define what “failure” is in terms of travel times; in other words, a threshold must be established. Then, one can count the number of times the threshold is not achieved or exceeded. These types of measures are synonymous with “on-time performance,” since performance is measured relative to a pre-established threshold. The only difference is that failure is defined in terms of how many times the travel time threshold is exceeded while on-time performance measures how many times the threshold is not exceeded.

In recent years, some non-U.S. reliability research has focused on another aspect of reliability: the probability of failure, where failure is defined in terms of traffic flow breakdown. A corollary is the concept of vulnerability, which could be applied at the link or network level and "is a measure of how vulnerable the network is to breakdown conditions."

- Project L03 used the distribution of travel times as the basis for defining all of its recommended reliability metrics (e.g., buffer index, failure-on-time measures, planning time index, 80th percentile travel time, skew statistic, and misery index).
- Project L04 (Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools) used this definition: "Models formulated in this research . . . [are] based on the basic notion that transportation reliability is essentially a state of variation in expected (or repeated) travel times for a given facility or travel experience. The proposed approach is further grounded in a fundamental distinction between (1) systematic variation in travel times resulting from predictable seasonal, day-specific, or hour-specific factors that affect either travel demand or network capacity, and (2) random variation that stems from various sources of largely unpredictable (to the user) unreliability."
- Project L07 (Evaluation of Cost-Effectiveness of Highway Design Features) used L03's definition.
- Project L11 (Evaluating Alternative Operations Strategies to Improve Travel Time Reliability) defined reliability as follows: "Travel time reliability is related to the uncertainty in travel times. It is defined as the variation in travel time for the same trip from day to day (same trip implies the same purpose, from the same origin, to the same destination, at the same time of the day, using the same mode, and by the same route). If there is large variability, then the travel time is considered unreliable. If there is little or no variability, then the travel time is considered reliable."

Reliability can be defined in two widely held ways. Each is valid and leads to a set of reliability performance measures that capture the nature of travel time reliability. The definitions are

1. The variability of travel times that occur on a facility or a trip over the course of time; and
2. The number of times (trips) that either "fail" or "succeed" in accordance with a predetermined performance standard or schedule.

In both cases, reliability (or more appropriately, unreliability) is caused by the interaction of factors that influence travel times: fluctuations in demand (which may be caused by daily or seasonal variation, or by special events), traffic control device operations, traffic incidents, inclement weather, work zones, and physical capacity (based on prevailing geometrics and traffic patterns).

The basic definition of travel time reliability (variability in travel times) can be extended to include the notion of predictability: What is the probability that a travel time for a facility or trip is within acceptable limits for the traveler, given that travel times are affected by interaction of demand fluctuations, traffic control devices, traffic incidents, inclement weather, work zones, and physical capacity. Travel time reliability also can be used to compare current conditions with historical conditions: Is the travel time today “typical” of what happens or is it better than the usual or near-worst case. Both corollaries are based on establishing the variability over time, as defined by the travel time distribution.

In a broader sense, reliability is a dimension or attribute of mobility and congestion. Traditionally, the dimensions of congestion are spatial (how much of the system is congested?), temporal (how long does congestion last?), and severity-related (how much delay is there or how low are travel speeds?). Reliability adds a fourth dimension: How does congestion change from day to day?

2.2 HOW CAN RELIABILITY BE MEASURED?

Reliability Performance Metrics

Travel time reliability relates to how travel times for a given trip and time period perform over time. For measuring reliability, a trip can occur on a specific highway section, any subset of the transportation network, or it can be broadened to include a traveler’s initial origin and final destination. The concepts discussed here apply to all of these units, as long as it is travel time over some distance that is being measured. Measuring travel time reliability requires that a sufficient history be present to track travel time performance.

From a measurement perspective, reliability is quantified from the distribution of travel times, for a given facility/trip and time slice, that occurs over a significant span of time; one year is generally long enough to capture nearly all of the variability caused by disruptions. A variety of different metrics can be computed once the travel time distribution has been established, including standard statistical measures (e.g., standard deviation, kurtosis), percentile-based measures (e.g., 95th percentile travel time, buffer index), on-time measures (e.g., percent of trips completed within a travel time threshold), and failure measures (e.g., percent of trips that exceed a travel time threshold). The reliability of a facility or trip can be reported for different time slices (e.g., weekday-peak hour, weekday-peak period, weekend).

A great deal of recent research has been targeted at developing appropriate ways of quantifying travel time reliability. This research has resulted in a number of metrics that may be used to quantify levels of reliability and the impacts of strategies intended to improve reliability. A good summary of reliability performance measures comes from SHRP 2 Project L03, which recommended several measures of reliability, as shown in Table 2.1. The recommendations were based on examining measures in use in the United States and other parts of the world. The list includes the skew statistic, as proposed by European researchers, as well as the 80th percentile travel time, which is especially sensitive to operations improvements and has been used in previous studies on the valuation of reliability.

TABLE 2.1. RECOMMENDED RELIABILITY PERFORMANCE METRICS FROM SHRP 2 L03 (*2*)

Reliability Performance Metric	Definition	Units
Buffer Index (BI)	The difference between the 95th percentile travel time and the average travel time, normalized by the average travel time The difference between the 95th percentile travel time and the median travel time, normalized by the median travel time	Percent
Planning Time Index	95th percentile travel time index (95th percentile travel time divided by the free-flow travel time)	None
Failure/On-Time Measures	Percent of trips with travel times less than 1.1 * median travel time *or* 1.25 * median travel time Percent of trips with space mean speed less than 50 mph; 45 mph; or 30 mph	Percent
80th Percentile Travel Time Index	80th percentile travel time divided by the free-flow travel time	None
Misery Index (Modified)	The average of the highest 5% of travel times divided by the free-flow travel time	None
Skew Statistic	The ratio of (90th percentile travel time minus the median) divided by (the median minus the 10th percentile)	None
Standard Deviation	Usual statistical definition	None

The travel time distribution in Figure 2.1 is a convenient way to visualize general congestion and reliability patterns for a highway section or trip. The x-axis is time (in minutes). The y-axis is the number of trips on the segment, which in this example is a 5.5-mile section of I-75 northbound from I-285 to Roswell Road in Atlanta, Georgia. The data were collected in 2010 and represent the 4:30 p.m. to 6:30 p.m. peak period. Figure 2.1 depicts the following measures.

- *Trips On-Time*. This represents the "failure/on-time measures," which can be calculated a few ways as described in Table 2.1. This example reflects the percent trips with the space mean speed of less than 45 mph. The space mean speed is the segment length (miles)/travel time (hours).
- *Average Travel Time Index* (TTI_{mean}). The average travel time divided by the free-flow travel time.
- *Free-Flow Travel Time*. The travel time on the segment under low-flow conditions. It can be measured from field data as the highest travel time for trips observed during uncongested periods. In this example, free-flow speed is 60 mph.
- *80th Percentile Travel Time Index* (TTI_{80}). 80th percentile travel time divided by free-flow travel time.
- *95th Percentile Travel Time Index* (TTI_{95}). 95th percentile travel time divided by free flow travel time. This is also known as the *planning time index* (PTI).

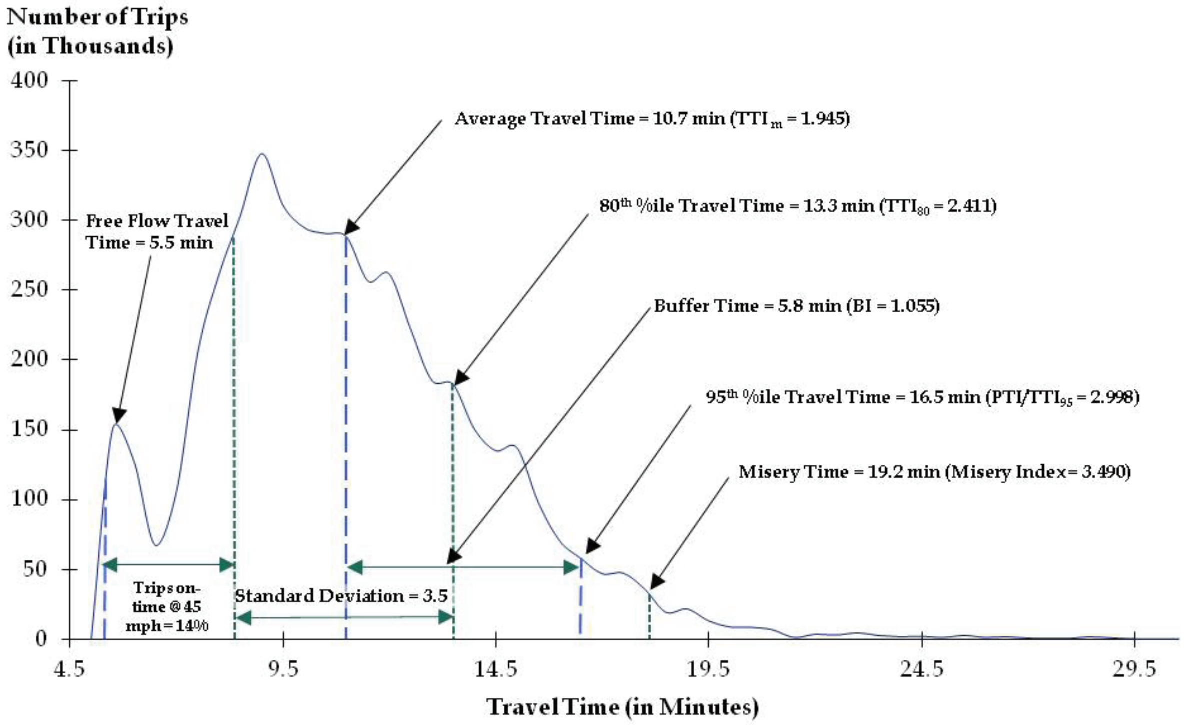


Figure 2.1. *Reliability metrics within a travel time distribution.*

- *Buffer Time*. The difference between the 95th percentile travel time and the average travel time.
- *Buffer Index*. The buffer time divided by the free flow travel time.
- *Misery Time*. The average of the highest 5% of travel times.
- *Misery Index*. The misery time divided by the free-flow travel time.
- Standard Deviation.

The skew statistic is illustrated separately in Figure 2.2. The following measures are depicted:

- *Skew Statistic Numerator.* The 90th percentile travel time minus the median travel time.
- *Skew Statistic Denominator.* The median travel time minus the 10th percentile travel time.
- *Skew Statistic*. The ratio of the numerator and denominator.

All of the listed measures can be calculated with the same detailed dataset. A discussion of these measures follows.

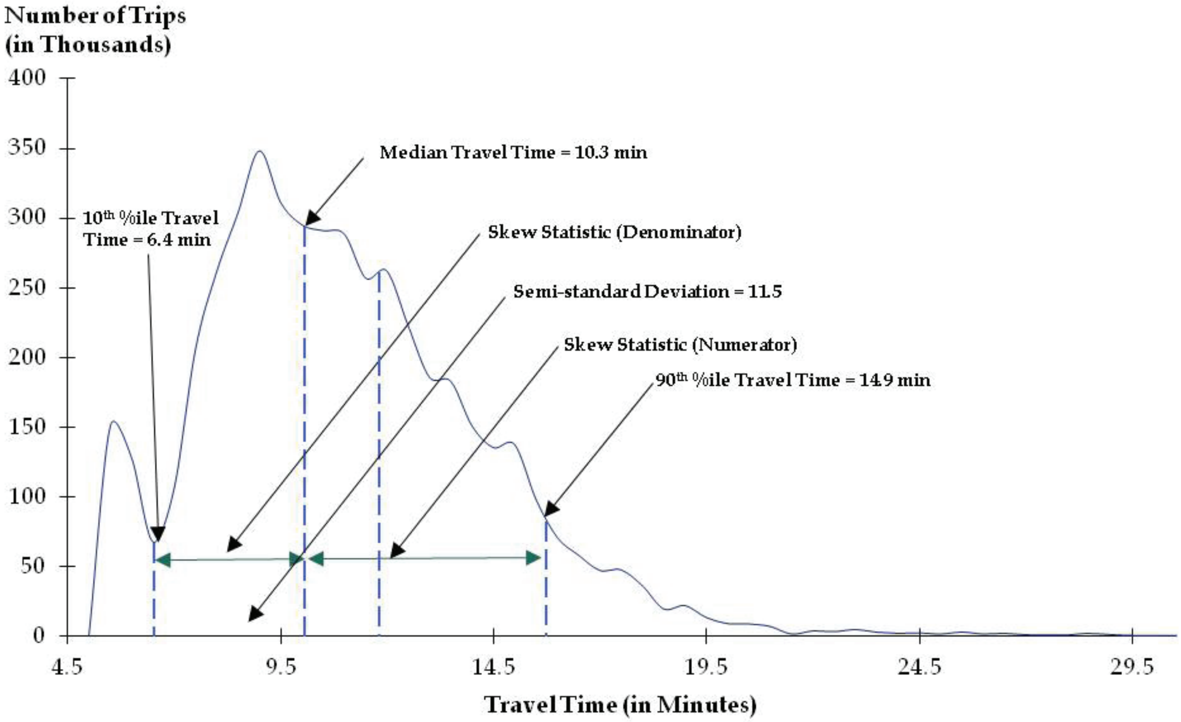


Figure 2.2. *Skew statistic within a travel time distribution.*

- The buffer index and planning time index are starting to be used in practice, primarily for performance monitoring applications. Users are cautioned that SHRP 2 L03 found that the buffer index can be an unstable indicator of changes in reliability; it can move in a direction opposite to the mean and percentile-based measures. This is because it uses both the 95th percentile and the median or mean travel time, and the percent change in these values can be different from year to year. If one changes more in relation to the other, counterintuitive results can appear. Florida Department of Transportation (DOT) found this to be the case and plans to stop using the buffer index for monitoring variability of congestion (see the Florida DOT case study for more information).
- Failure/On-Time measures are defined (1) in reference to the median travel time (used to indicate "typical" conditions for a trip) and (2) in relation to predetermined performance standards based on the space mean speed (SMS) of the trip.
  - Because their construction is binary (a trip either passes or fails the condition), these measures can be insensitive to small changes in underlying performance. Therefore, they have been defined with multiple thresholds so that changes in performance can be more easily detected.
  - The median-based measures are constructed as on-time measures while the SMS measures are constructed as failure measures.

- The 80th percentile travel time index has not been widely used. However, SHRP 2 L03 found that it can be more sensitive to operational changes than the 95th percentile and recommended its inclusion. Further, one of the more reliable past studies of reliability valuation used the difference between the 80th and 50th percentile travel times as the indicator of reliability (*2*).
- The misery index, in its current definition, is close to the 97.5 percentile travel time index.
- Although not specifically tested in L03, the skew statistic may also suffer from the instability phenomenon as the buffer index and planning time index.
- Standard deviation was not part of the L03 set of measures, but it should be added because of its use in applications. SHRP 2 Project C04 and Project L04 use standard deviation as one of the terms in expanded utility functions that are used to predict traveler behavior and several past studies of reliability valuation have used standard deviation as the measure that is valued.

To provide a sense of the range of values of reliability performance metrics, Table 2.2 presents reliability indices for a cross-section of Florida freeways for the p.m. peak period (4:30 p.m. to 6:30 p.m.). The measures were calculated using spot speeds that were inverted into travel time rates (min/mi). Four travel time indices were calculated based on a free-flow speed definition of the posted speed limit plus 5 mi/h. The buffer time index is based on the 95th percentile speed and the mean speed, and the misery index is based on the average of the highest 5% of travel times and a free-flow travel time based on the posted speed limit minus 5 mi/h.

Measuring Performance on Corridors and Areas

All of the reliability performance metrics in this report are based on travel times on individual roadway segments. In many cases, analysts will need reliability metrics for corridors or areas made up of multiple segments. The proper way to go from lower spatial levels to higher ones is to roll up each of the segment metrics (e.g., travel time index) into a corridor index or an area index using a weighted average based on vehicle-miles traveled (VMT). This equation is defined in the *2011 Congested Corridors Report* (*4*) where the indices calculated on individual segments are weighted together by VMT from each segment to generate a corridor index.

Trends in Reliability

Reliability is a new concept for the transportation profession. Practitioners have very little experience with developing reliability measures and relating them to everyday experience. Reliability is complex and its proper measurement requires multiple metrics. Specifically, the distribution of travel times is used to characterize reliability, and the use of multiple measures provides a clearer picture of the size and shape of the distribution.

It can be confusing to interpret multiple reliability performance metrics. Some metrics may appear to indicate improvement in reliability between alternatives, while others may not. The SHRP 2 L03 report *Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies* provides an illustrative example

TABLE 2.2. FLORIDA FREEWAY RELIABILITY STATISTICS (*3*)

Location	50% TTI	80% TTI	90% TTI	95% TTI (PTI)	Buffer Time Index	Misery Index
I-95 NB at NW 19th St.	1.00	1.36	1.69	2.01	2.02	2.22
I-95 SB at NW 19th St.	1.08	1.19	1.58	2.01	1.86	2.48
I-95 NB, S of Atlantic Blvd.	1.03	1.28	1.73	2.23	2.16	2.74
I-95 SB, S of Atlantic Blvd.	1.10	1.36	1.89	2.37	2.15	2.93
SR 826 NB at NW 66th St.	2.40	2.82	3.07	3.35	1.39	3.69
SR 826 SB at NW 66th St.	1.01	1.28	2.63	4.06	4.02	4.62
SR 826 WB, W of NW 67th Ave.	1.04	1.08	1.21	1.77	1.70	2.10
SR 826 EB, W of NW 67th Ave.	0.98	1.00	1.02	1.04	1.07	1.10
I-4 EB, W of World Dr.	0.97	1.04	1.06	1.08	1.12	1.12
I-4 WB, W of World Dr.	1.02	1.09	1.49	1.90	1.86	2.22
I-4 EB, W of Central Florida Pkwy.	1.06	1.13	1.18	1.31	1.24	1.56
I-4 WB, W of Central Florida Pkwy.	1.05	1.36	1.63	1.81	1.72	2.03
I-275 NB, N of MLK Jr. Blvd	1.45	1.71	1.91	2.16	1.49	2.58
I-275 SB, N of MLK Jr. Blvd.	0.97	1.01	1.04	1.12	1.15	1.28
I-275 NB, N of Fletcher Blvd.	1.05	1.07	1.11	1.21	1.16	1.35
I-275 SB, N of Fletcher Blvd.	0.96	0.98	0.99	1.00	1.04	1.01
I-10 EB, E of Lane Ave.	0.93	0.96	0.98	0.99	1.07	1.01
I-10 WB, E of Lane Ave.	0.97	1.10	1.24	1.46	1.51	1.87
I-95 NB, S of Spring Glen Rd.	1.04	1.09	1.26	1.77	1.70	2.00
I-95 SB, S of Spring Glen Rd.	1.16	1.30	1.42	1.60	1.38	1.88
Minimum	0.93	0.96	0.98	0.99	1.04	1.01
Average	1.11	1.26	1.51	1.81	1.64	2.09
Maximum	2.40	2.82	3.07	4.06	4.02	4.62

Notes: TTI = travel time index based on the percentile speed indicated and a free-flow speed defined as (posted speed plus 5 mi/h); PTI = planning time index; Buffer Time Index = index based on the 95th percentile and mean travel speeds; Misery Index = index based on the average of the highest 5% of travel times and a free-flow travel time based on (posted speed plus 5 mi/h). N = north, S = south, E = east, W = west, NB = northbound, SB = southbound, EB = eastbound, WB = westbound.

of the challenges in interpreting the varied results of a reliability analysis. The L03 report is excerpted in Appendix B, and the entire report can be found online at http://www.trb.org/Main/Blurbs/166935.aspx.

2.3 WHY IS MEASURING RELIABILITY IMPORTANT?

Fluctuations in travel time variability may be traced to a number of causes, including incidents, inadequate base capacity, demand variability, special events, traffic signals (controls), inclement weather and work zones. Figure 2.3 presents an overview of the relative contribution each of these sources makes on overall congestion in a typical urban area.

Historically, the transportation planning process has focused on assessing system performance by comparing the base system capacity with average demand on a typical day in order to generate average travel times that formed the basis for comparison and prioritization of system investments. As shown in Figure 2.3, however, this approach misses analyzing many other causes of congestion, and thus vastly underestimates actual congestion.

Further, many operational strategies, such as incident management systems, often have a disproportionate impact on those causes of nonrecurring congestion. Therefore, the traditional approach of only assessing average travel times does not capture the impact of operational strategies. For example, Knoxville has implemented closed-circuit television (CCTV) and a fleet of trucks to clear incidents, but these programs are not designed to address typical day congestion and therefore cannot be assessed using typical benefit calculations.

To illustrate the importance of considering the full range of travel times, Figure 2.4 shows two analyses that were performed comparing the expected level of benefits from the San Diego Integrated Corridor Management (ICM) system deployments. The first graph shows the benefits estimated for the system during typical conditions (average demand, good weather, no incidents). The second graph shows the benefits of the system during incident conditions. Projected benefits of the ICM are more than double ($10.8 million versus $5.1 million) during these nonrecurring events; failure

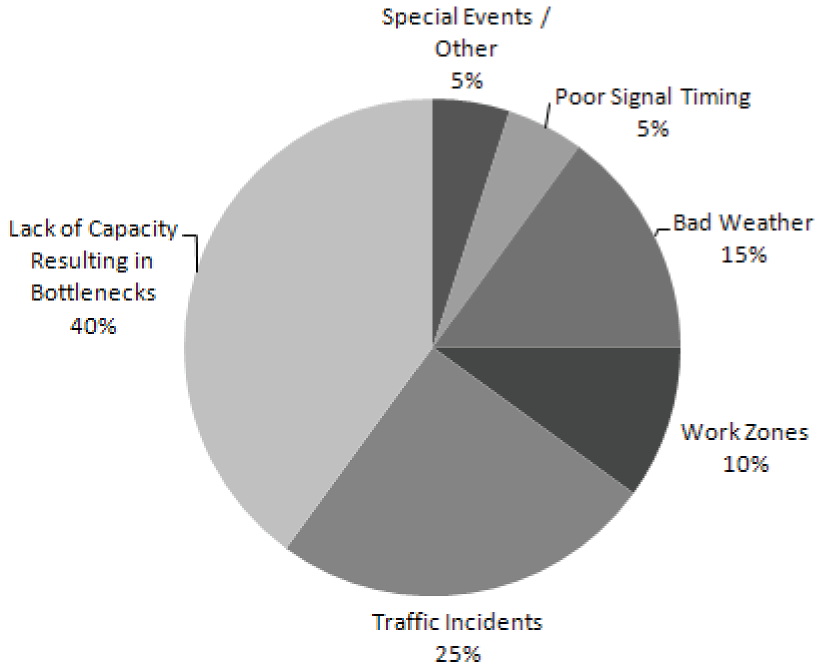


Figure 2.3. *Causes of travel delay (4).*

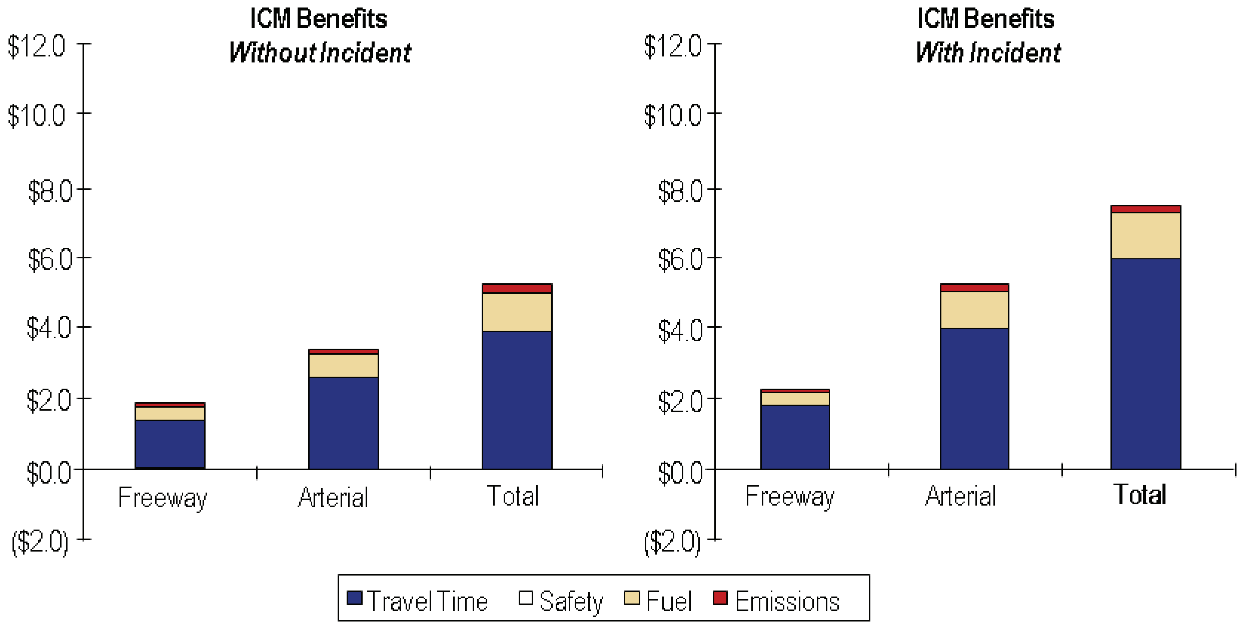


Figure 2.4. *Comparison of project benefits during typical versus incident conditions.*

to consider these impacts would result in a greatly understated estimation of project value.

Likewise, if practitioners ignore the impacts of congestion on nontypical days, or fail to account for situations where specific congestion mitigation strategies (e.g., incident management systems) may produce the majority of their benefits on nontypical days, results of their analysis may be greatly distorted and may lead to suboptimal investment decisions.

2.4 STRATEGIES FOR IMPROVING RELIABILITY

Past research suggests a clear link between the implementation of transportation improvement strategies and an actual improvement in travel time reliability. This linkage allows planners and programmers to use reliability metrics in transportation planning, programming, and budgeting processes. For example, a major result of the SHRP 2 L03 research was that demand (volume) is an extremely important determinant of reliability, especially in terms of its relation to capacity. From the intertwined relationship between demand, capacity, and disruptions, the L03 research team concluded that *reliability is a feature or attribute of congestion, not a distinct phenomenon*. Because any influence on congestion will lead to unreliable travel, reliability cannot be considered in isolation. Implications from this finding include the following.

- All strategy types will improve both average congestion and reliability (i.e., average congestion is reduced and reliability is improved).

- It is clear that traditional capacity projects improve reliability, and failure to account for this effect in economic analyses has resulted in the exclusion of these impacts in the accounting of the full benefits to users.
- Management and operations strategies designed to minimize disruptions (e.g., incident management) will affect congestion only when those disruptions appear. Demand management strategies, such as pricing, also will lead to improvements in reliability.

Additional Capacity Strategies

All things being equal, additional capacity (in relation to demand) means that the roadway is able to absorb the effects of some events that would otherwise cause disruption.

Examples of highway or arterial capacity improvements that can increase reliability include new roadways, roadway widening, street connectivity, grade separations, high-occupancy vehicle (HOV) and managed lanes, and multimodal corridors. Examples of transit capacity improvements include new rail lines, new bus lines, new busways and bus rapid transit (BRT), additional service on existing routes, neighborhood circulator routes, and park-and-ride lots. Examples of freight capacity improvements include truck only lanes and rail improvements.

Systems Operations and Management Strategies

As nonrecurring congestion (NRC) is the principal source of unreliability on the nation's roads, the SHRP 2 L06 project identified strategies by which transportation agencies can adjust their institutional architecture—including culture, organization and staffing, resource allocation, and partnerships—to support more effective transportation systems operations and management (SO&M).

SO&M applications to date have typically been centered within the larger highway jurisdictions; they are also used for major arterials and rural routes. SO&M strategies cited in the SHRP 2 L06 report include the following.

- Incident management, including multijurisdictional, integrated corridor management in response to crashes, breakdowns, hazardous material spills, and other emergencies that are responsible for up to 30% to 35% of delay—and most unreliability—in major metropolitan areas;
- Road weather management in response to heavy rain, wind, snow and ice, which can constitute from 5% to 10% of delay in some areas;
- Work zone traffic management focused on traffic control plans to minimize the impacts of reduced capacity, constituting anywhere from 10% to 20% of total delay;
- Special-events planning and management to accommodate event patrons and bystanders with minimal traffic disruption; and
- Active traffic management using lane use and speed control to minimize flow disruption and incidents, as well as managing diversions and the operation of diversion routes, in response to both recurring and nonrecurring congestion.

Other examples of highway improvements that can improve reliability include ramp metering and electronic toll collection. For arterials, other examples include access management, advanced signal systems, and parking restrictions. Operational improvements for transit include automatic vehicle location (AVL), advanced scheduling, and transit signal priority. Operational improvement strategies for freight include electronic screening and clearance programs.

Demand Management Strategies

A number of categories of demand management strategies address reliability.

- Travel alternatives such as alternate hours of travel, alternative work schedules, telecommuting, pedestrian and bicycle facilities, alternative fare strategies, and public education campaigns on driving.
- Land use strategies such as smart growth policies, pedestrian and bicycle connections, transit stop and station design, transit-oriented design, and parking strategies.
- Pricing strategies such as high occupancy toll (HOT) lanes, time-of-day pricing, activity center pricing, and parking pricing.
- HOV strategies such as rideshare matching, transportation management associations, vanpools, priority parking for HOVs, parking cash out, guaranteed ride home program, and instant ridesharing.
- Transit strategies such as subsidized fares, transit-oriented design, enhanced transit stops and stations, trip itinerary planning, transportation management associations, and transit security systems.
- Freight strategies such as truck only toll (TOT) lanes, lane restrictions, and delivery restrictions.

2.5 HOW TO INCORPORATE RELIABILITY INTO A BENEFIT–COST ANALYSIS

A benefit–cost analysis is a systematic, quantitative method of assessing the benefits and costs of potential investments or projects through monetized values to produce a ratio. As such, a ratio greater than one is considered economically efficient. The objective is to facilitate the more efficient allocation of resources through well-informed decision making. A common method to establish a priority ranking of projects is using an incremental benefit–cost analysis. In this analysis, the total incremental benefits of a project are compared with incremental costs of implementing the project. The real power of incremental benefit–cost analysis is that it can be used to determine the best actions to take given a budget constraint. If needed, net benefits can be determined to provide an aggregate view of the investment. Net benefits is defined as the sum of all benefits minus the sum of all costs, which provides an absolute measure of benefits (total dollars), rather than the relative measures provided by benefit–cost ratio.

As travel time reliability performance measures and strategies are incorporated into the transportation planning and programming process, the effects need to be included in the monetized benefits to better understand the project's need given funding constraints. To integrate travel time reliability into a benefit–cost analysis, the following data are needed:

- A measure for travel time reliability;
- A value of time related to reliability;
- A method for predicting future reliability; and
- A method for estimating changes in reliability due to a project.

See Chapter 6 in this technical reference for a step-by-step guide for calculating a reliability measure appropriate for monetary valuation within a benefit–cost analysis, as well as a description of how the outputs from various analysis methods and tools may be used to support these analyses. Furthermore, Section 3.1 of the technical reference provides a description of considerations and criteria for best matching analysis methods with the needs of the practitioner.

2.6 REFERENCES

1. Turner, S., R. Margiotta, and T. Lomax. *Final Report—Monitoring Urban Freeways in 2003: Current Conditions and Trends from Archived Operations Data*. Report FHWA-HOP-05-018. Federal Highway Administration, U.S. Department of Transportation, 2004. http://mobility.tamu.edu/mmp/FHWA-HOP-05-018/, quoted in Cambridge Systematics, Inc. *SHRP 2 Project L03 Final Report: Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies*. Strategic Highway Research Program (SHRP 2), Transportation Research Board of the National Academies, 2010.
2. Cambridge Systematics, Inc. *SHRP 2 Project L03 Final Report: Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies*. Strategic Highway Research Program (SHRP 2), Transportation Research Board of the National Academies, 2010.
3. Table 37-11, Proposed Travel Time Reliability Supplemental (Chapter 37), *Highway Capacity Manual 2010*. Transportation Research Council of the National Academies, 2012.
4. *2011 Congested Corridors Report*, Texas Transportation Institute, College Station, Texas, 2011, p. B-13.

3

DESCRIPTION OF TOOLS AND METHODS FOR ESTIMATING RELIABILITY

This chapter summarizes available types of tools and methods that may be used to estimate reliability measures. Chapter 4 provides a comparison of the tools and methods to aid in tool and method selection.

It is not the intent of this chapter to provide a comprehensive analysis of all the potential tools and methods that may be used to estimate reliability, or a comprehensive guide to all the possible applications of these tools and methods. Instead, the focus of this chapter is to provide descriptions of general categories of these tools and methods and to provide guidance and examples of how they may be applied best.

The subsequent chapters provide summaries of the following four broadly defined categories of reliability analysis tools and methods:

- Sketch-planning methods;
- Post-processing methods;
- Simulation or multiresolution methods; and
- Monitoring and management tools and methods.

In the discussion of each category of tool and method, the guidance includes the following:

- Overview of the tool or method;
- Available tools and methods;
- Discussion of appropriate situations in which to apply the tools and methods;

Color versions of the figures in this chapter are available online:
http://www.trb.org/Main/Blurbs/168856.aspx

- Discussion of the general input data required; and
- Discussion of the output performance measures and format.

The summary section that follows describes the categories of tools and methods and identifies relative strengths and weaknesses of using them.

3.1 SUMMARY OF ANALYSIS TOOLS AND METHODS

In this technical reference, four types of reliability tools and broadly defined methods are considered:

- *Sketch-Planning Methods*. These are analysis methods intended to provide quick assessment of reliability (and the impacts of projects affecting reliability) using generally available data as inputs to the analysis. These are the least resource-intensive of the analysis methods and produce order-of-magnitude results that are often used in early planning stages.
- *Model Post-Processing Methods*. These analysis methods focus on applying customized analysis routines to data from a regional travel demand model to generate more specific estimations of travel time reliability measurements. They benefit from the travel demand model's robust network and supply-and-demand conditions. The most common of these methods is based on analysis from the ITS Deployment Analysis System (IDAS) tool, developed by the Federal Highway Administration (FHWA), which estimates incident-related congestion (a major component contributing to travel time variability).
- *Simulation or Multiresolution Methods*. These methods make use of an advanced traffic simulation model's ability to test and assess the driver's behavior and reactions to nonrecurring events. Multiresolution methods often take advantage of the integration of several standard modeling tools (e.g., microsimulation and travel demand models) to combine different tools' abilities to assess shorter-range and longer-range impacts of various congestion mitigation strategies. For reliability assessments, these simulation and multiresolution methods are often combined with multiscenario analysis (described in Section 5.5), whereby models are run with several alternative conditions that represent logical variations in travel demand, weather conditions, incident occurrence, presence of work zones, or other factors influencing nonrecurring congestion.
- *Monitoring and Management Tools and Methods*. These tools and methods are intended to provide analysis of real-time and archived traffic data. They differ from the aforementioned methods as they primarily target assessing past conditions rather than forecasting future conditions; however, these tools and methods may play a significant role in providing data for forecasting methods.

Multiscenario Methods may be developed and applied on top of any of the analysis methods described previously to provide additional assessment of reliability during nontypical conditions. In a multiscenario approach, several alternative baseline conditions are identified representing logical variations in travel demand, weather conditions, incident occurrence, presence of work zones, or other factors influencing nonrecurring congestion. Reliability is then estimated individually for each of the scenarios (typically using one of the methods previously described) and then annualized or averaged using the relative frequency of the conditions as a weighting scheme. Monitoring and management tools and methods typically provide the background data to develop the alternative conditions scenarios.

As the spectrum in Figure 3.1 suggests, the tools and methods are presented in the order of least to most complex; however, the comparison is not clear-cut. Sketch planning is often the least complex, but is limited in that it cannot explicitly capture reliability from the limited, static data required to use these methods and tools. However, the methods and tools in this technical reference provide ways of capturing the variability that is inherent to reliability. As the state of the practice in reliability analysis advances, practitioners and analysts should be moving toward dynamic tools such as simulation or multiresolution modeling. If a simulation model already exists, it is a relatively simple exercise to use it for a reliability analysis. Monitoring and management tools are intentionally omitted from this figure, as they are not directly used for alternatives analysis.

Table 3.1 presents some general strengths and weaknesses for the four categories of tools and methods for calculating reliability.

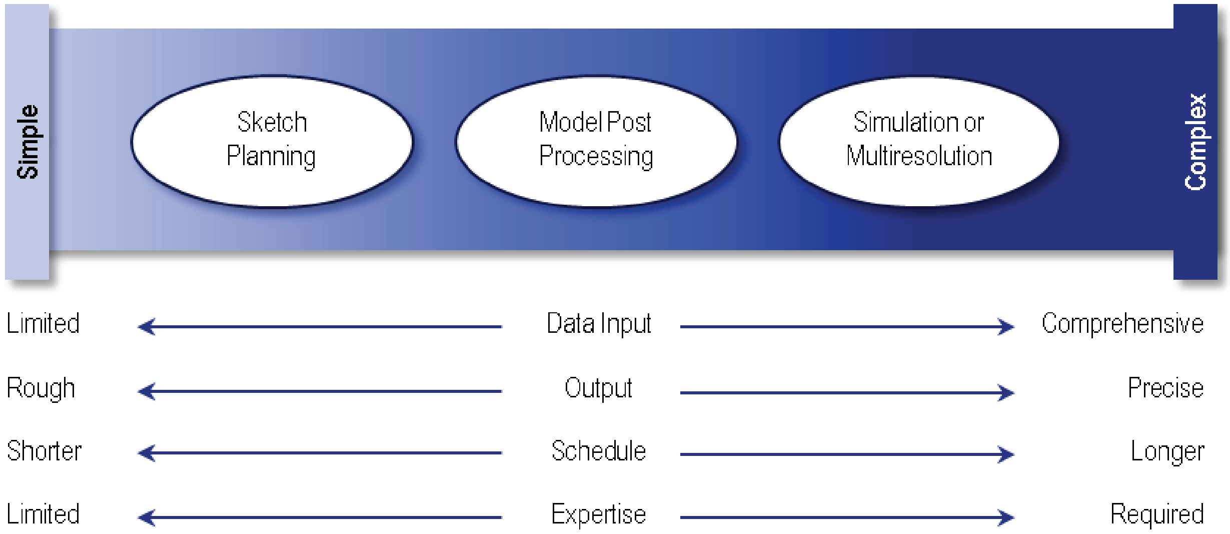


Figure 3.1. *Spectrum of reliability analysis tools and methods.*

TABLE 3.1. OVERVIEW OF ANALYSIS TOOLS AND METHODS FOR CALCULATING RELIABILITY

Tool or Method	Strengths	Weaknesses
Sketch-Planning Methods	• Easy and fast analysis • Use generally available data • Can be used in data-poor environments where other tools and data are unavailable	• Limited reliability metrics • Based on assumptions of average conditions • Generally applied to aggregated conditions • Do not explicitly capture reliability because they are based on static conditions
Model Post-Processing Methods	• Based on local data from the established regional model • Overcomes some of the limitations in using travel demand models for estimating reliability • More robust than simple sketch-planning methods	• Requires an underlying regional travel demand model (or simulation model) • Can be time-consuming to integrate the methods with the regional travel model • Limited reliability metrics • Requires multiple model runs to assess variations in demand
Simulation or Multiresolution Methods	• Provides the most robust forecast of travel-time variability under all the expected travel conditions (when combined with a multiscenario approach) • Combining travel demand models with simulation models provides most accurate assessment of long- and short-term impacts on reliability • Typically provides the greatest opportunity to assess operational improvements	• Requires that underlying regional travel demand model and simulation model are available • Time- and resource-intensive to develop the models and conduct analysis • Assessment of underlying causes of congestion requires accurate performance data collected over a long time period • Requires multiple model runs for each scenario • Significant cost to set up, calibrate, and complete analysis
Monitoring and Management Tools and Methods	• Typically easy and fast analysis once system is developed • Based on real-world (not forecast) data • Ability to assess real-time conditions • Ability to assess historical trends • Ability to compare influencing factors (e.g., incidents, weather) and actual traffic conditions retroactively	• Analysis capability limited by data availability and quality of underlying data • Development costs may be moderate to high (each system needs to be configured to the regional data availability) • Not capable of testing future strategies to address congestion

Several SHRP 2 projects are developing analytic methods for estimating reliability directly, from a variety of resolution scales, from sketch planning to microscopic simulation:

- SHRP 2 L03: developed statistically derived reliability equations based on empirical data. Two types of models were developed: "data-poor," which requires only an estimate of recurring delay, and "data-rich," which requires information on demand, capacity, incident characteristics, and weather conditions. The data-poor equations have also been adapted for use in Projects C10B and C11.

- SHRP 2 L04: is developing a simulation-based approach to reliability estimation, using a combination of mesoscopic and microscopic models. It fits into the "Simulation or Multiresolution Methods" category.
- SHRP 2 L07: is developing a hybrid approach for predicting reliability based on combining microsimulation experiments with the data-rich equations from L03.
- SHRP 2 L08: is developing a scenario-based approach combined with macroscopic modeling methods for inclusion of reliability into the *Highway Capacity Manual*. Project L08 also fits into the "Simulation or Multiresolution Methods" category, but its analytic engine is macroscopic in nature.
- SHRP 2 L11: did not develop reliability prediction methods but did develop an original approach to valuing reliability based on options theory.

Table 3.2 presents some ideas on which of the methods are most appropriate for different scales of analysis. Note that benefit–cost analysis could be part of any of these analysis types.

Further linkage between this project and other SHRP 2 projects is provided in Table A.2 in Appendix A. Until these procedures find their way into widespread use in the profession, the guidance in this technical reference may be used, as it is meant to be applied within the existing modeling frameworks at transportation agencies.

The methods were validated through case studies of agencies that have begun to think about reliability but have not fully incorporated it into their planning practices. Key findings from the case study results are referenced throughout the technical reference.

Additional resources and tools are listed in Appendix A.

TABLE 3.2. ANALYSIS TYPES MATCHED TO RELIABILITY PREDICTION TOOLS

Analysis Type/Scale	Supporting Tools
Sketch Planning	L03 reliability prediction equations
Project Planning	L07 hybrid method where data inputs are limited L08 multiscenario methods where additional data are available and more resolution in results is desired
Facility Performance	L08 multiscenario methods most directly applicable L04 preprocessor (simulation manager) and post-processor (trajectory processor) could be used, then the performance of an individual facility can be isolated
Travel Demand Forecasting	L03 reliability prediction equations and L07 method can be adapted as post-processors L08 multiscenario methods could be used to develop custom functions for post-processing
Traffic Simulation	L04 preprocessor (simulation manager) and post-processor (trajectory processor) most appropriate L08 scenario generator can be adapted

3.2 SKETCH-PLANNING METHODS

Overview

Sketch-planning methods are designed to provide a quick analysis of reliability using minimum input data. These methods are intended to provide order-of-magnitude estimates of reliability metrics based on assumptions regarding the relationships observed in other areas between reliability metrics and other standard performance metrics (e.g., volume to capacity ratios, mean travel times).

Sketch-planning methods are intended to be used by a wide range of practitioners and often require little experience to apply. Typically, the data used as input to the sketch-planning methods represent basic data that are available and relatively easy to compile at most transportation agencies. Therefore, these methods can be applied quickly and with less analysis resources than the other methods described in this reference.

The ease of use of these methods comes at a cost, however, in that the sketch-planning methods are usually limited in the robustness of their analysis, output metrics, and configurability to particular conditions. Sketch-planning methods are most appropriately applied to situations requiring quick assessments of order-of-magnitude reliability impacts, such as preliminary screening of alternatives or quantifying reliability impacts in a region to promote consideration of particular mitigating strategies.

In analyses requiring more confidence in the level of impacts or more capability to configure the analysis to actual conditions, such as evaluating optimal strategies or conducting design work, many agencies will move past the sketch-planning methods in favor of more robust model post-processing and simulation methods, described in subsequent sections. Sketch planning may still have a role in these analyses, particularly for agencies without access to the underlying traffic data or models used in these more robust techniques.

Available Tools and Methods

Sketch-planning methods vary in complexity, input data, and output metrics. The SHRP 2 L03 project is the most recent sketch-planning method made available for travel time reliability analysis and is the main method described in this reference. Before the SHRP 2 work, states and regions have undertaken other individual efforts to quantify reliability using sketch-planning methods. Perhaps the most prevalent of examples was completed by the Florida Department of Transportation (FDOT) to assess the reliability of their freeway system on a statewide basis using archived data. FDOT developed a methodology to predict travel time reliability as a function of various changes in the system, such as incident removal times, work zone occurrences, and weather.

The SHRP 2 L03 project developed analysis methods for evaluating reliability from generally available performance metrics. This technical reference presents the sketch-planning method based on the Project L03 data-poor prediction equations. These equations were based on continuously collected empirical measurements of travel time from numerous locations around the country. They indicate that reliability metrics can be effectively predicted from the overall mean travel time index. Figure 3.2 shows an example of these relationships.

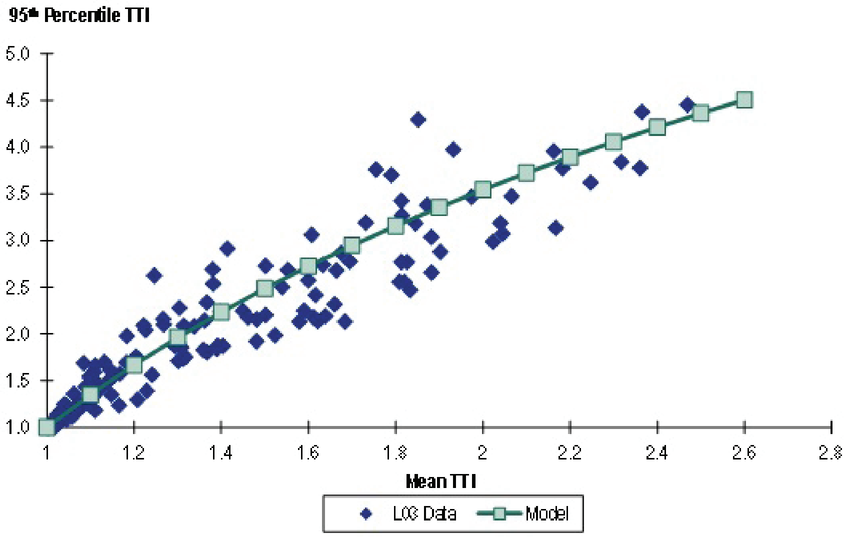


Figure 3.2. *Relationship of mean travel time to 95th percentile travel time index.*

The overall mean travel time index in Figure 3.2 includes all of the sources of possible variations in travel time (e.g., incidents, weather, special events), because the measurements were taken over the course of an entire year. This reflects both recurring and nonrecurring congestion conditions. However, data collection efforts and traditional models usually represent typical day or recurring conditions only. For these cases, the sketch-planning method includes calculations to convert the average travel time from these sources to the overall mean travel time.

The L03 sketch-planning method relies on making an estimate of the overall mean travel time index (TTI_{mean}). This starts with an estimate of the recurring-only average travel time, which is obtained from field measurements or agency models or derived using segment volume and capacity. Then, the overall mean travel time index is estimated in one of two ways:

- Using a simple relationship from the L03 research; or
- A more detailed method that estimates incident delay and combines it with recurring delay.

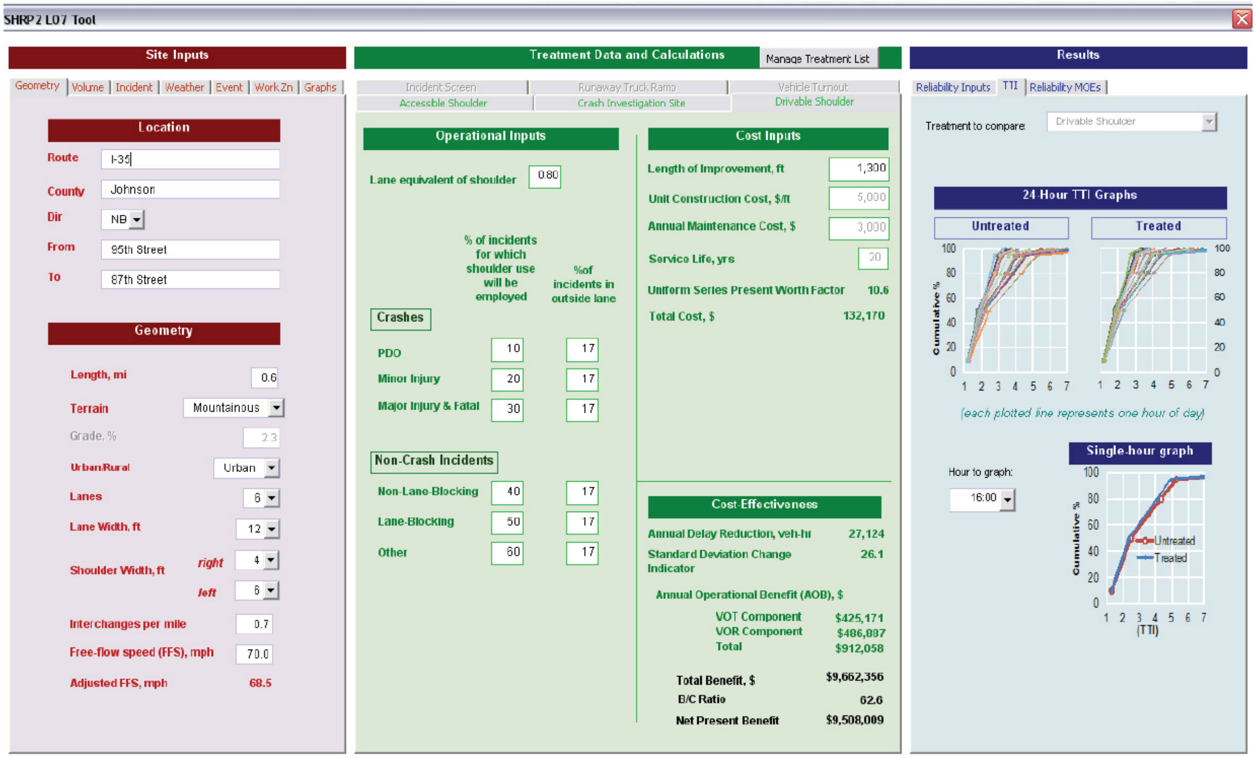
Further technical details about these methods are provided in Section 5.1.

Another example of a sketch-planning tool is being developed under the SHRP 2 L07 project, Evaluating Cost-Effectiveness of Highway Design Features. This work is centered on evaluating capacity improvements that mitigate congestion and delay caused by incidents, weather events, work zones, special events, demand fluctuations, and traffic control devices. Interestingly, the treatments available in this tool are essentially geometric design improvements, rather than intelligent transportation systems (ITS) solutions. Treatments available for evaluation in the tool are categorized as "directly design-related" and "indirectly design-related." Directly design-related treatments are those that involve the physical infrastructure of the highway and roadside (e.g., drivable shoulders, runaway truck ramps, and median crossovers). Indirectly, design-related treatments are those that either support or are supported by the physical infrastructure, but alone may be considered ITS treatments. For example, contraflow lanes involve the physical design of the managed lanes plus variable message signs for the treatment to function as intended. Although the contraflow lanes themselves are directly design related, the variable message signs are indirectly design related.

Figure 3.3 shows a screen shot of the SHRP 2 L07 tool, which is capable of producing the following reliability measures: PTI, buffer index; 50th percentile, buffer index; mean; skew statistic; and misery index. The inputs include site data (i.e., geometry, volume, incidents, weather, events, and work zones) and treatment data related to operations and costs.

Appropriate Situations for Applying the Tools and Methods

Sketch-planning methods are appropriate for use in analysis situations that require relatively quick analysis of reliability, on an aggregate scale, using generally available performance data. These methods are most often applied to aggregate sections of the transportation network (sections versus individual roadway links) and to date have most often been applied to freeway sections, as opposed to arterial facilities.



Location

Route	I-35
County	Johnson
Dir	NB
From	95th Street
To	87th Street

Geometry

Length, mi		0.6
Terrain		Mountainous
Grade, %		2.3
Urban/Rural		Urban
Lanes		6
Lane Width, ft		12
Shoulder Width, ft	right	4
	left	6
Interchanges per mile		0.7
Free-flow speed (FFS), mph		70.0
Adjusted FFS, mph		68.5

Operational Inputs

Lane equivalent of shoulder 0.80

	% of incidents for which shoulder use will be employed	%of incidents in outside lane
Crashes		
PDO	10	17
Minor Injury	20	17
Major Injury & Fatal	30	17
Non-Crash Incidents		
Non-Lane-Blocking	40	17
Lane-Blocking	50	17
Other	60	17

Cost Inputs

Length of Improvement, ft	1,300
Unit Construction Cost, $/ft	5,000
Annual Maintenance Cost, $	3,000
Service Life, yrs	20
Uniform Series Present Worth Factor	10.6
Total Cost, $	132,170

Cost-Effectiveness

Annual Delay Reduction, veh-hr	27,124
Standard Deviation Change Indicator	26.1
Annual Operational Benefit (AOB), $	
VOT Component	$425,171
VOR Component	$486,887
Total	$912,058
Total Benefit, $	$9,662,356
B/C Ratio	62.6
Net Present Benefit	$9,508,009

Treatment to compare: Drivable Shoulder

Hour to graph: 16:00

Figure 3.3. *Screenshot of the SHRP 2 L07 tool.*

Sketch-planning methods generally provide order of magnitude reliability estimation, and as such, are appropriate for conducting assessments of system deficiencies and preliminary screening of alternatives. Sketch-planning methods also can be applied on preferred alternatives to supplement an initial screening process in situations where resources limit the ability to conduct a robust analysis using more complex tools or methods.

In general, sketch-planning methods are appropriate for evaluating additional capacity alternatives. When evaluating demand management alternatives, it is prudent to incorporate a travel demand model as input to sketch-planning methods. Similarly, when evaluating operational improvements, simulation model outputs can be used as input to sketch-planning methods.

Input Data

The strength of many sketch-planning methods is that they may be applied in a data-poor environment, where only limited operational data are available. At the most basic level, segment free-flow speed and distance are required. The next step is to obtain average travel time, which can be accomplished one of three ways: (1) record in the field, (2) extract from a model, or (3) estimate using segment volume and capacity.

Output Metrics

Given the high-level assessment approach, output metrics for sketch-planning tools are generally limited in their range (i.e., types of metrics available) and their disaggregation (i.e., level of detail for individual facilities). The most common outputs from sketch-planning methods are indices such as the buffer index or the planning time index (as defined in Table 2.1) for corridor or systemwide evaluation. These metrics may be further broken down into reliability for specific causes of congestion, such as incidents or work zones. Use of the SHRP 2 L03 method provides an estimate of the total delay (recurring plus nonrecurring), which may be used in providing relative comparison of congestion levels for different analysis alternatives or may be monetized for use in a benefit–cost analysis.

3.3 MODEL POST-PROCESSING TOOLS AND METHODS

Overview

Travel demand models are some of the most widely applied tools in assessing transportation system performance and analyzing the potential impacts of transportation system investments. Travel demand models have been extremely limited historically, however, in their ability to analyze reliability. The foundation of most travel demand models is based on the analysis of a typical day (i.e., a day with average travel demand, fair weather, no construction, and no incidents). The analysis of this typical day, therefore, produces little variability within the model to analyze the reliability of travel times in other nontypical or nonrecurring conditions.

To overcome these limitations, several post-processing tools and methods have been developed to assist practitioners in conducting an analysis of reliability using their established travel demand models. An advantage of these post-processing methods is that the analysis is based on the calibrated regional travel model outputs that are generally accepted and widely used in the region for planning efforts, adding credibility to the results and allowing the results to be easily incorporated within the overall planning process.

The Florida DOT and the Southeast Michigan Council of Governments (SEMCOG) are both adopting post-processing tools to their regional travel demand models for the purpose of determining travel time reliability. The Florida DOT is using the reliability metrics in the strategic, decision-making and project delivery levels of the planning process (see the Florida DOT case study for more information). SEMCOG, under limited budget and time constraints, is using its post-processing tool to analyze the benefits of alternative funding levels for specific representative corridors, the results of which were multiplied to report regionwide benefits (see SEMCOG case study for more information).

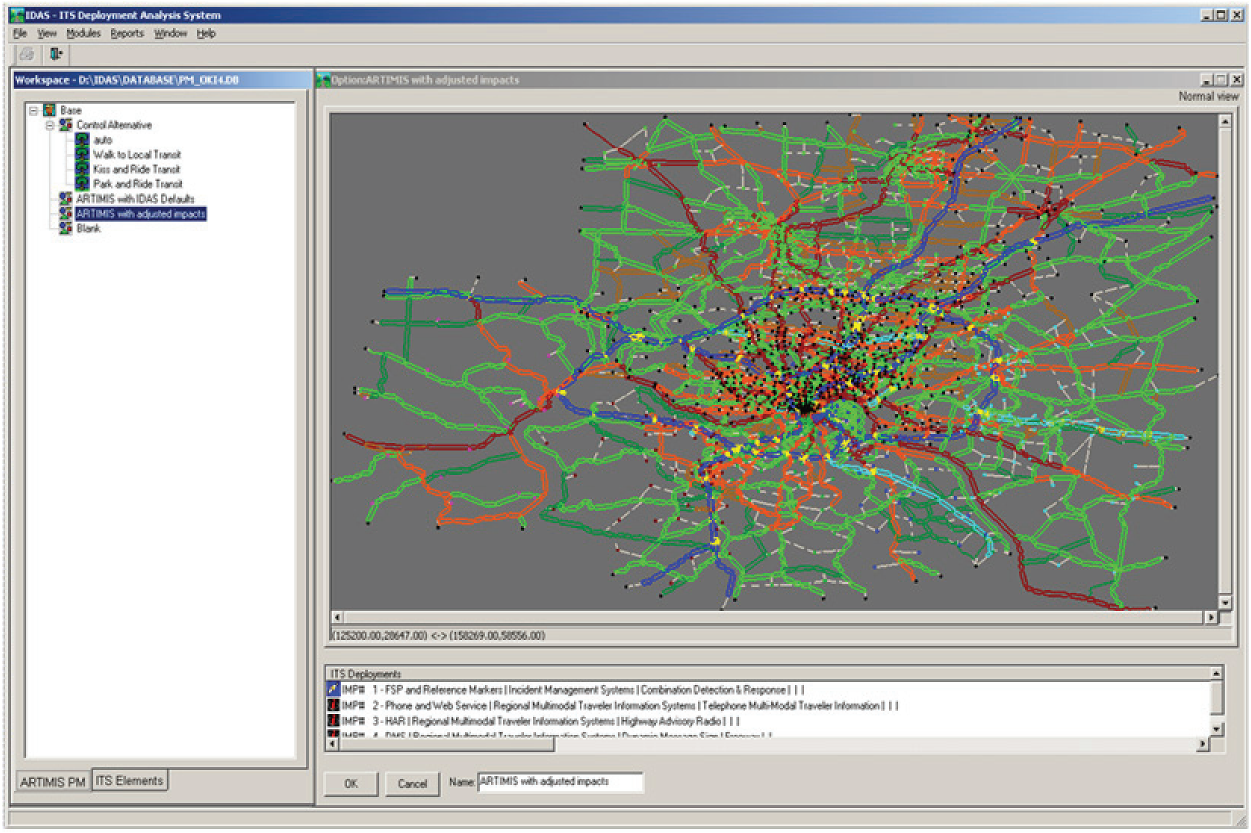
Available Tools and Methods

The most widely applied example of model post-processing tools is the ITS Deployment Analysis System (IDAS) tool developed by the FHWA. This software tool is designed to pull in data from a regional planning model in order to perform analysis on the relative benefits and costs of various ITS strategies. The IDAS tool, shown in Figure 3.4, was one of the first tools to specifically incorporate an analysis of reliability. In the case of IDAS, travel time reliability represents only incident-related delay, and the analysis is limited to only freeway links. Therefore, the analysis provides only a partial estimation of total travel time reliability internal to the model.

In calculating network-level or link-level reliability, the IDAS tool utilizes a series of lookup tables containing the anticipated amount of incident-related delay that would be encountered on a particular freeway link per vehicle-miles traveled (VMT) on the link. The data are stratified by volume to capacity (V/C) ratio (the higher the V/C ratio, the higher the anticipated amount of incident-related delay per VMT) and by the number of lanes on the facility (increases in the number of lanes generally brings about lower anticipated amounts of incident-related delay). The stated capacity in the IDAS lookup tables represents a Level of Service (E).

A variety of lookup tables is available in IDAS depending on the length of the analysis period (e.g., peak hour, two-hour peak period, three-hour peak period, four-hour peak period, and daily). Table 3.3 presents the IDAS lookup table for a one-hour peak. The table shows that the vehicle-hours of incident delay per vehicle-mile increases as the V/C ratio increases. It also shows that the incident delay decreases as the number of lanes increases. Additional lookup tables showing values for other analysis periods are presented in Appendix C.

In conducting the analysis, the IDAS tool calculates the V/C for each freeway link, looks up the value of vehicle-hours of incident delay in the appropriate table, and multiplies that value with the reported VMT for the particular link. The incident delay from all network freeway links is then summed to provide the network measure for incident-related delay.



Workspace - D:\IDAS\DATABASE\PM_OKI4.D0

(125200.00,28647.00) <-> (158269.00,58556.00)

ITS Deployments

IMP# 1 - FSP and Reference Markers | Incident Management Systems | Combination Detection & Response | | |

IMP# 2 - Phone and Web Service | Regional Multimodal Traveler Information Systems | Telephone Multi-Modal Traveler Information | | |

IMP# 3 - HAR | Regional Multimodal Traveler Information Systems | Highway Advisory Radio | | |

Name: ARTIMIS with adjusted impacts

Figure 3.4. *Screenshot of the ITS Deployment Analysis System (IDAS) model post-processing tool.*

The direct calculation of delay from weather or construction events is not specifically provided within IDAS. It is possible to structure an analysis to capture this additional variability by applying a multiscenario approach, as further described in Section 5.5. In a multiscenario approach, individual scenarios are analyzed separately to estimate the likely traffic conditions that would occur for each day with similar weather and/or construction activity. The results of the individual scenarios are then annualized by applying a weight to each scenario representing how many days a year that scenario would be anticipated to occur in a typical year. Appendix D provides additional information on completing a multiscenario analysis based on probability of occurrence.

Although IDAS is the most well-known of the post-processing tools and methods for calculating reliability, many other similar methods exist. The Florida Department of Transportation has modified the IDAS approach to work with its standard travel demand structure within the state. The customized application is known as the Florida ITS Evaluation tool, or FITSEval. A screenshot of FITSEval is shown in Figure 3.5.

Other agencies have simply developed basic programs to apply the incident delay rates from the IDAS lookup tables to performance data from their own models. For example, the Metropolitan Transportation Commission (MTC), the regional planning

TABLE 3.3. TRAVEL TIME RELIABILITY: RATES FOR 1-H PEAK VEHICLE-HOURS OF INCIDENT DELAY PER VEHICLE-MILE

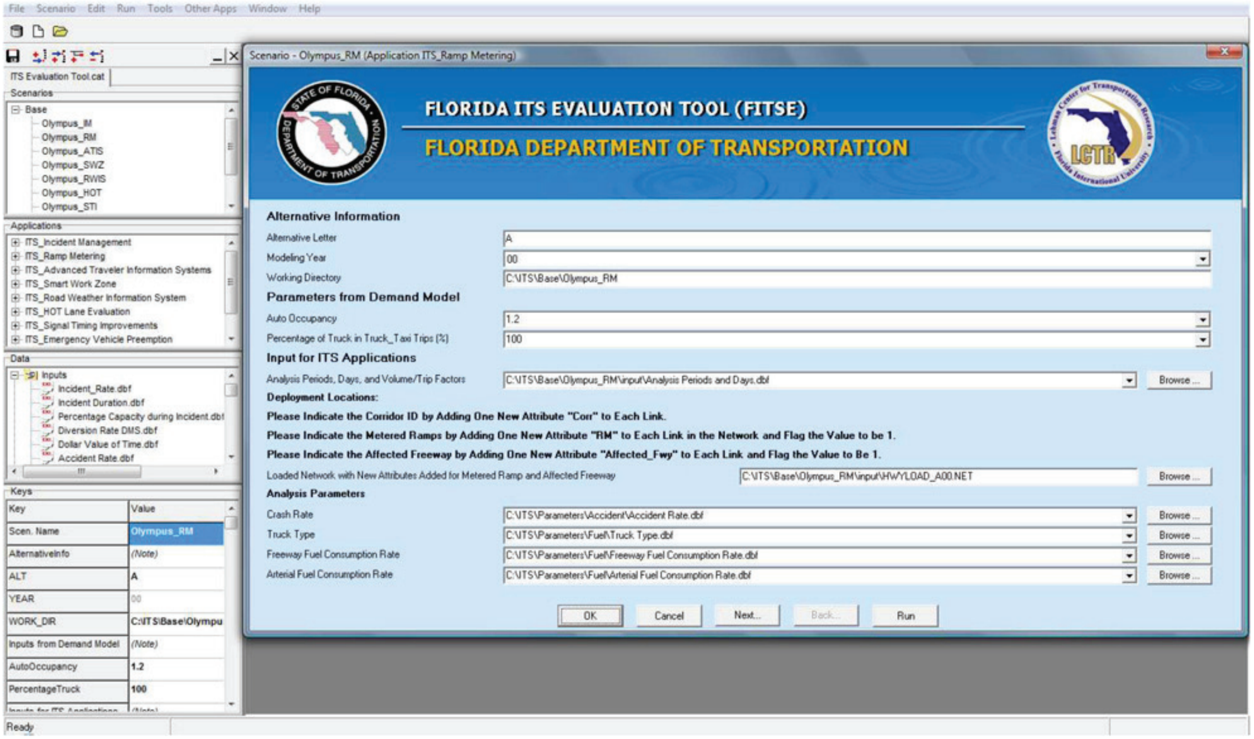
Volume/1-h Level of Service Capacity	Number of Lanes		
	2	3	4+
0.05	3.44E-08	1.44E-09	4.39E-12
0.1	5.24E-07	4.63E-08	5.82E-10
0.15	2.58E-06	3.53E-07	1.01E-08
0.2	7.99E-06	1.49E-06	7.71E-08
0.25	1.92E-05	4.57E-06	3.72E-07
0.3	3.93E-05	1.14E-05	1.34E-06
0.35	7.20E-05	2.46E-05	3.99E-06
0.4	0.000122	4.81E-05	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	0.01986	0.01744	0.01368

agency for the San Francisco Bay Area, has developed relatively simple SAS programming to look up and apply the incident delay measures to data directly from their travel demand model on a link-by-link basis. This customized program allows MTC to estimate incident-related delay without linking their model directly to the IDAS software. Several agencies have applied similar post-processing methodologies through the application of customized routines within their model framework. For limited applications (e.g., analyzing only a few links), a simple program could be set up in a spreadsheet to estimate reliability using the lookup table data provided in Appendix C.

Appropriate Situations to Apply the Tools and Methods

Model post-processing methods can be applied in any situation in which a regional travel demand model is available. These methods should be used in analyses when the estimation of incident-related delay is the desired output.

In general, IDAS is most appropriate for evaluating operational improvements and some demand management strategies. IDAS is capable of analyzing over 60 different types of ITS investments. These ITS components may be deployed individually or in



Key	Value
Scen. Name	Olympus_RM
AlternativeInfo	(Note)
ALT	A
YEAR	00
WORK_DIR	C:\ITS\Base\Olympu
Inputs from Demand Model	(Note)
AutoOccupancy	1.2
PercentageTruck	100

Alternative Information

Alternative Letter: A
Modeling Year: 00
Working Directory: C:\ITS\Base\Olympus_RM

Parameters from Demand Model

Auto Occupancy: 1.2
Percentage of Truck in Truck_Taxi Trips (%): 100

Input for ITS Applications

Analysis Periods, Days, and Volume/Trip Factors: C:\ITS\Base\Olympus_RM\input\Analysis Periods and Days.dbf

Deployment Locations:

Please Indicate the Corridor ID by Adding One New Attribute "Corr" to Each Link.

Please Indicate the Metered Ramps by Adding One New Attribute "RM" to Each Link in the Network and Flag the Value to be 1.

Please Indicate the Affected Freeway by Adding One New Attribute "Affected_Fwy" to Each Link and Flag the Value to Be 1.

Loaded Network with New Attributes Added for Metered Ramp and Affected Freeway: C:\ITS\Base\Olympus_RM\input\HWYLOAD_A00.NET

Analysis Parameters

Crash Rate: C:\ITS\Parameters\Accident\Accident Rate.dbf
Truck Type: C:\ITS\Parameters\Fuel\Truck Type.dbf
Freeway Fuel Consumption Rate: C:\ITS\Parameters\Fuel\Freeway Fuel Consumption Rate.dbf
Arterial Fuel Consumption Rate: C:\ITS\Parameters\Fuel\Arterial Fuel Consumption Rate.dbf

Figure 3.5. *Screenshot of Florida ITS Evaluation tool.*

combination with one another (2). These components are categorized into 11 areas based on the National ITS Architecture:

1. Arterial traffic management systems;
2. Freeway management systems;
3. Advanced public transit systems;
4. Incident management systems;
5. Electronic payment systems;
6. Railroad grade crossing monitors;
7. Emergency management services;
8. Regional multimodal traveler information systems;
9. Commercial vehicle operations;
10. Advanced vehicle control and safety systems; and
11. Supporting deployments.

Using a post-processing tool or method is typically more time-consuming than the sketch-planning method; however, the output is more detailed and can easily be fed into the sketch-planning equations for further analysis. IDAS also is capable of providing travel times, crash and emission rates, and other impacts that may be needed for a larger analysis.

Input Data

Input data for model post-processing methods include link-level data that are typically available in most regional travel demand models (or simulation models). These data primarily include loaded roadway volumes, base facility capacities, and basic geometric data (e.g., number of facility lanes). The loaded model networks can represent peak hour, peak period, or daily analysis. If the IDAS software is used directly, some additional model data may be required to enable IDAS to replicate the model assignment procedures within the software. These additional data include modal trip tables, volume-delay curve assumptions, and other model parameters. In addition to the base case, where the IDAS model reflects current roadway conditions, the alternatives must be sufficiently detailed to be coded into the IDAS model network.

If a multiscenario approach is selected, the probability of certain weather conditions (number of days per year with rain, snow, etc.) and/or construction activities is needed to assign a weight to each scenario that would be anticipated to occur in a typical year.

Output Metrics

The primary reliability output from using the IDAS methodology or one of its derivatives is the estimated number of hours of vehicle delay caused by incidents within the analysis period. The direct output is incident delay, which can be used as an input to the sketch-planning method to get the buffer index and the planning time index. IDAS includes a benefit–cost analysis component, and therefore is capable of producing a monetized value for reliability as a function of incident delay.

3.4 SIMULATION OR MULTIRESOLUTION METHODS

Overview

Traffic simulation models can provide the most robust analysis of traffic performance under varying conditions. They have the ability to measure impacts of events, such as excessive demand and traffic incidents, as well as short-term traveler behavioral changes, such as queuing effects, diversion patterns, and responses of specific individuals to traveler information. They are also capable of outputting very detailed performance metrics, including the breakout of performance into discrete time slices to allow analysts to evaluate conditions during the congestion buildup, at the peak of congestion, and as congestion dissipates. Other tools and methods often are limited to evaluating average conditions across a single period of time. As such, simulation models are a powerful tool for assessing travel time reliability and the impacts on strategies in mitigating nonrecurring congestion.

Using simulation methods by themselves, however, has some limitations. Due to these limitations, simulation methods are often combined with less discrete models in a multiresolution approach. Typically, the less discrete model used in a multiresolution approach is a regional travel demand model, and the more discrete model is a microscopic simulation model. Mesoscopic simulation models, which sit between travel demand and microsimulation models in terms of complexity, are becoming more prevalent. A multiresolution model can include any two or more of these model resolutions.

A majority of the level of effort for this category of tools and methods lies in the development and calibration of the models. If a calibrated simulation model already exists for the study area, a detailed reliability analysis can be completed in a relatively short period.

Available Tools and Methods

Two methods are discussed in this document. The first is the simple method, which uses the model results from a simulation model in combination with the SHRP 2 L03 sketch-planning method. The SHRP 2 L03 method uses equations based on average travel time to calculate reliability metrics. In the case of simulation models, travel time is a direct output that can be used as an input to these equations. For more information on the SHRP 2 L03 method, refer to the sketch-planning sections of this document (Sections 3.2 and 5.1). The second method includes a multiscenario approach and allows for a more refined analysis of operational strategies within the simulation model itself. The remainder of this section focuses on the multiscenario method.

The multiscenario method was employed as part of the U.S. Department of Transportation's (DOT) Integrated Corridor Management (ICM) program. U.S. DOT recently sponsored the comprehensive analysis of ICM benefits at several pioneer sites, including San Diego, Dallas, and Minneapolis–Saint Paul. The analysis techniques developed for this assessment represent a significant step forward in the evaluation and estimation of reliability.

To conduct the analysis, each of the regions integrated their regional travel demand model with a simulation model representing the specific corridor where the ICM deployments were to be implemented. Multiple iterations of the combined models were then used to estimate both the long-term and short-term impacts of the ICM strategies, as well as to evaluate the performance of the system under varying weather and incident conditions. Figure 3.6 presents a general overview of the analysis approach used in the ICM analyses.

A key part of the ICM analysis approach was the evaluation and improved understanding of the causes of variability. Three causes were identified: demand, incidents, and weather. Archived data were analyzed to determine how much influence each of the causes had on the total delay in the corridor. Figure 3.7 shows the results of the analysis for the Dallas study.

Each scenario used in the multiscenario method represents a combination of the three causes of travel time variability in varying severity: demand (high, medium, low); incidents (none, minor, major); and weather (normal, inclement). Various simulation model runs were assigned to each of these scenarios. The distribution of the model runs were assigned based on the likelihood of the particular scenario occurring, with more model runs assigned to those scenarios with the greatest likelihood of occurrence. When all the specified model runs were completed, they were combined to generate estimates of travel time, delay, travel time reliability (95th travel time percentile), and travel time variance.

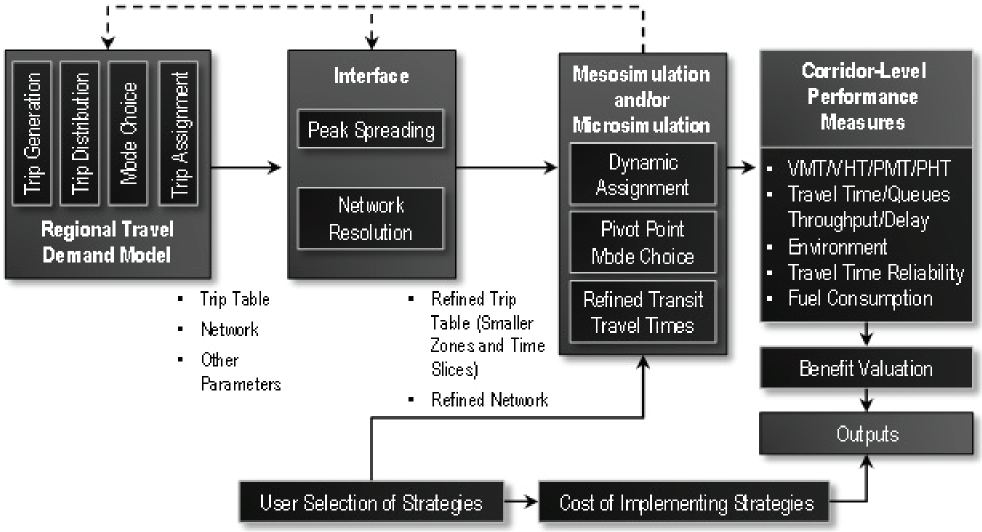


Figure 3.6. *Overview of ICM multiresolution analysis approach.*

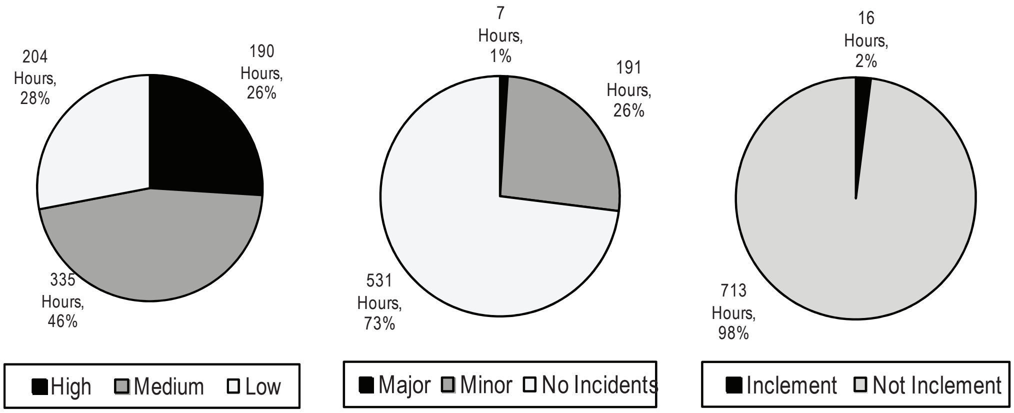


Figure 3.7. *Sample analysis of existing traffic conditions on US-75 in Dallas.*
Notes: Cluster analysis conducted for year 2007, weekday, 6:00 a.m–9:00 a.m., southbound direction only. Historical weather data obtained from www.weatherunderground.com. Incident and demand data obtained from DalTrans Traffic Management Center. Incident data include accidents, minor breakdowns, debris, etc.

Appropriate Situations for Applying the Tools and Methods

Because of the immense level of effort and resources required to build and calibrate a simulation model, it is not recommended to apply this method solely for evaluating reliability, unless the demand for detail and accuracy is very high. Instead, this method is recommended where simulation models already exist or a reliability analysis is part of a wider project analysis for which a simulation model will be developed.

The use of simulation models in this approach requires that the analysis area be relatively constrained to a small subarea of the regional network, usually a corridor. Expansion of the analysis to a broader region would require significantly more resources. In situations where a regional reliability assessment is desired, the analyst may want to consider conducting a multiresolution analysis on one or more representative corridors and extrapolating the results to other similar facilities.

Simulation methods are best suited to the analysis of operational improvement and additional capacity strategies, but these methods can also be used in the analysis of demand management alternatives.

Input Data

Minimally, the input data requirements include the regional travel demand model and the input data required for the additional development and calibration of a simulation model. This typically includes higher-detail roadway geometry than would be available in a travel demand model, traffic signal timings, and more discrete data on travel speeds and volumes, among other data. Further, robust archived data (demand, incident, and weather) are required to conduct the multiscenario analysis of conditions occurrence distribution.

If simulation models have previously been developed for the study corridor or subarea, significant savings in data collection, model development, and model calibration costs may be realized. In fact, if the simple method is chosen and a simulation model already exists, no additional data are needed. The multiscenario method requires the distribution (in days per year) of the likelihood of each scenario: demand (high, medium, low); incidents (none, minor, major); and weather (normal, inclement) as further described in Section 5.3.

Output Metrics

Given the disaggregated nature of the output data from simulation models, it is possible to produce reliability metrics for smaller time slices (e.g., 15-min periods) rather than daily statistics. The reliability metrics are based on a distribution of average travel times from each scenario. For the simple method, the travel times can be used as input to the sketch-planning equations.

Emerging Methods

Significant progress has been made on two SHRP 2 projects relevant to traffic modeling tools: L08 (Incorporation of Travel Time Reliability into the *Highway Capacity Manual*) and L04 (Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools).

SHRP 2 L08

The SHRP 2 L08 project is nearing completion of a methodology for measuring travel time reliability that is a proposed new chapter for the *Highway Capacity Manual 2010* (HCM). It includes a mathematical tool using the multiscenario approach to determine the reliability of freeways and urban streets. The tool determines the probability of occurrence for each scenario based on probabilities of each cause of congestion—demand, weather, and so on. The probabilities can be input by the user based on local data, or default values can be used. Each scenario is then run through the appropriate computational engine, FREEVAL-RL or STREETVAL, for analysis. The results of these analyses are aggregated into a travel time distribution from which the appropriate reliability measure or measures can be reported. Figure 3.8 illustrates this process.

In place of a simulation model, the HCM reliability tool uses FREEVAL or STREETVAL, spreadsheet-based traffic flow models for freeway and arterial streets, respectively. The use of the HCM reliability tools is not as complex as simulation models. The combination of traffic flow models and the multiscenario method makes an ideal tool for practitioners who want the precision of the multiscenario method but lack the resources needed for simulation models. There are, however, very specific data requirements for the HCM tool, which will be detailed in Chapter 36, a proposed chapter written as part of the SHRP 2 L08 project for inclusion in an update to the HCM 2010. The chapter also will include a method for translating planning time index (PTI) into HCM level of service (LOS), a measure that decision makers accustomed to HCM terminology may be more comfortable using. The HCM measure represents the LOS achieved on the facility 95% of the time. As FREEVAL and STREETVAL produce a travel time distribution, these tools are capable of producing the full set of reliability measures discussed in Chapter 2 of this document.

SHRP 2 L04

The main objective of the SHRP 2 L04 project is to develop the capability to produce reliability performance measures as output from planning and simulation models. The first phase of this project was completed in 2010 and included a framework and functional requirements for the inclusion of travel time reliability estimates in transportation network modeling tools (microscopic, mesoscopic, or macroscopic models) using

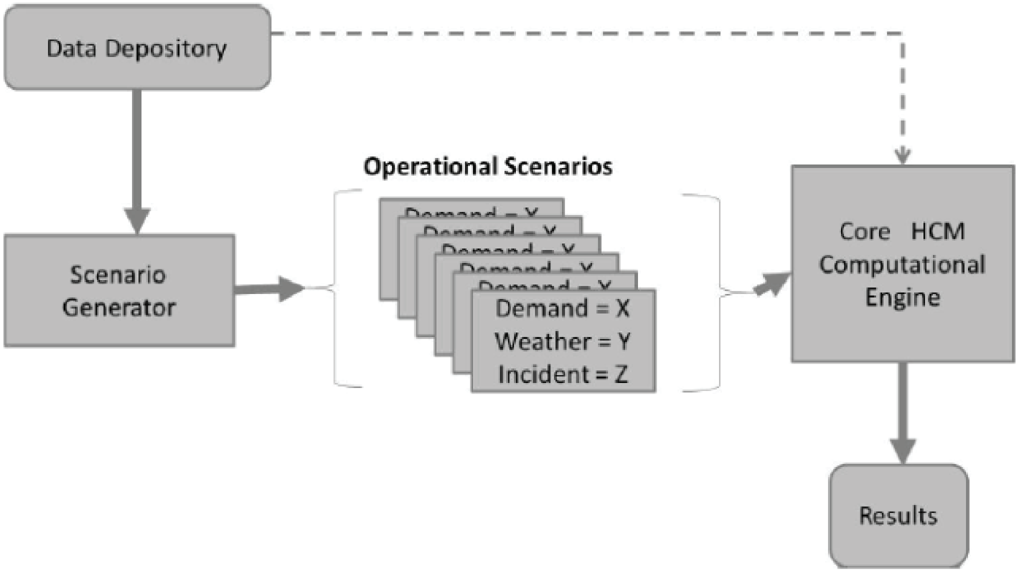


Figure 3.8. *HCM reliability methodology*

the multiscenario approach. The modeling framework includes a preprocessor, which prepares a set of simulation input files, and a post-processor, which extracts various reliability performance measures from the simulation output.

The preprocessor, known as the Scenario Manager, will provide the ability to construct scenarios with different combinations of external events, both demand-related as well as supply-related. It also allows random generation, through Monte Carlo sampling, of hypothetical scenarios for analysis and design purposes. The Scenario Manager will enable the simulation of scenarios over multiple days, hence reflecting daily fluctuations in demand, both systematic and random.

The post-processor, known as the Trajectory Processor, will extract reliability-related measures from the vehicle trajectory output of simulation models. Independent measurements of travel time at link, path, and O-D level can be extracted from the vehicle trajectories to construct the travel time distribution. As discussed in Chapter 2, all the reliability measures (such as buffer index, skew statistic, frequency with which congestion exceeds a particular threshold, etc.), can be derived from the travel time distribution.

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.

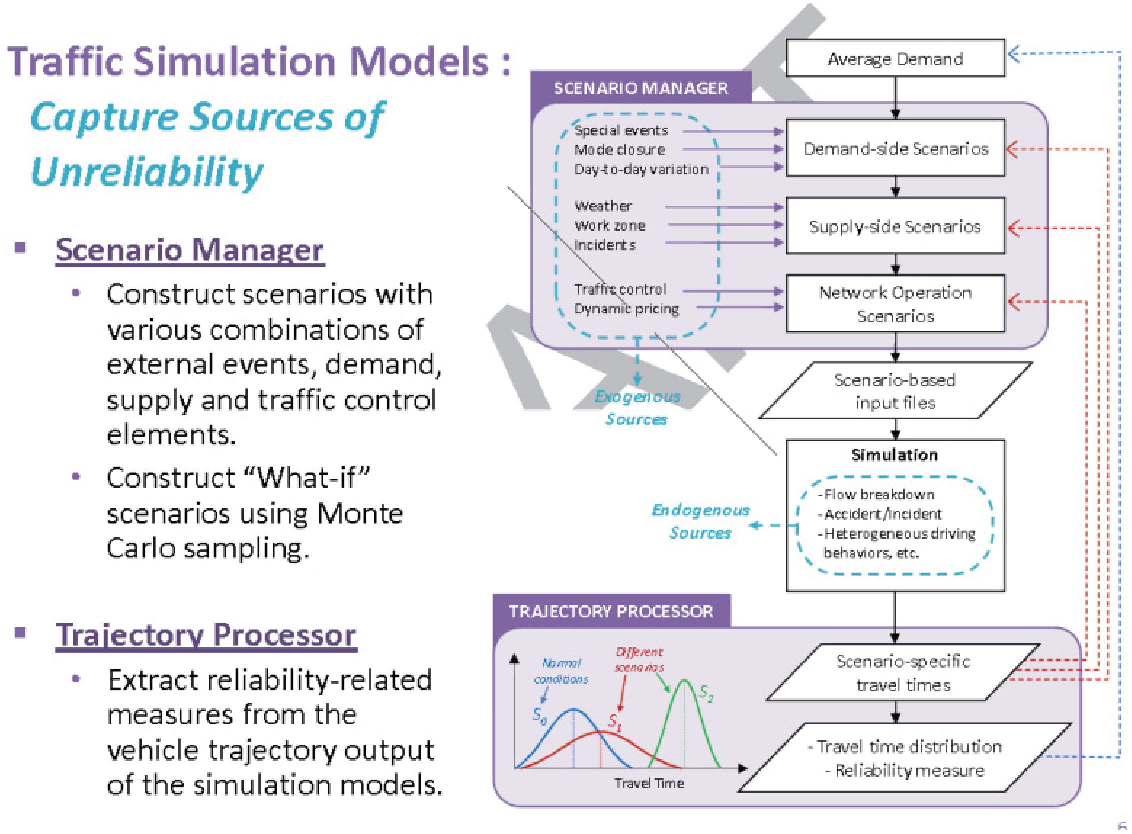
Figure 3.9 illustrates the updated framework for this evolving procedure, including possible feedback loops that imply that the simulation outputs might affect the scenario generation scheme in the Scenario Manager and update basic inputs such as the average travel demand.

The second phase of SHRP 2 L04 is under way; it includes testing and demonstration of the framework.

3.5 MONITORING AND MANAGEMENT TOOLS AND METHODS

Overview

The tools and methods discussed up to this point in this chapter have focused on the ability to forecast reliability under various operating conditions or forecast the impact of strategies intended to affect reliability performance measures. In addition to the need to forecast conditions, there is also the need to monitor current conditions and to look back at historical conditions to assess reliability trends over time. Monitoring and management tools and methods are largely designed to provide these capabilities by collecting, analyzing, and reporting on data.



Traffic Simulation Models : *Capture Sources of Unreliability*

- Scenario Manager
  - Construct scenarios with various combinations of external events, demand, supply and traffic control elements.
  - Construct "What-if" scenarios using Monte Carlo sampling.
- Trajectory Processor
  - Extract reliability-related measures from the vehicle trajectory output of the simulation models.

Figure 3.9. *Proposed simulation modeling framework for reliability* (3).

A number of agency planning and operations departments have already developed or are in the process of developing monitoring and management tools. For example, the Los Angeles County Metropolitan Transit Authority (LAMTA) is developing an arterial performance and reliability measurement system using data sources from traditional traffic monitoring sources and alternative sources such as traffic control devices and transit automatic vehicle location (AVL) systems (see the Los Angeles Metropolitan Transit Authority case study for more information).

Monitoring and management tools and methods are intended to provide the analysis of real-time and archived traffic data. They could be as simple as spreadsheets or more comprehensive, such as commercial off-the-shelf software tools or customized software products developed within an agency or by a contractor for the agency.

In many cases, these tools sit on top of an existing archived traffic data system and provide the analyst with the capability of accessing, analyzing, and comparing data stored in these data repositories. These data may include, but are not limited to,

- Automated spot traffic data (e.g., loop, acoustic, radar traffic detectors) including volume, speed, occupancy, and other data;
- Travel time data (probe data);

- Incident logs;
- Crash data;
- Operational data (e.g., logs of messages displayed on variable message signs, 511 calls or alerts); and
- Weather data.

An effective monitoring and management tool has two major components: a back-end data repository and front-end user interface. The data maintained in these repositories are invaluable in assessing the causes of congestion as well as the effectiveness of various strategies for addressing these underlying causes. Monitoring and management tools and methods provide the mechanism for effectively accessing and analyzing this data.

The tools and methods are used for accessing archives, comparing trends, reporting performance measures, creating dashboards, and creating historical data for planning and operations modeling. The tools may also be used in real time when compared with archived data to make day-to-day operational decisions. Visualization of the data often plays a key role in reporting results.

Available Tools and Methods

A broad range of tools monitor network performance and manage the data, and many tools are customized specifically for each organization. This chapter summarizes the common methods to compile and analyze data from various data sources. A number of methods for collecting traffic data are presented in Appendix E.

Several resources are available that can be used in the development of data archives for performance monitoring or other applications. These resources are substantive; thus, a reference is provided here without detail.

- The *National ITS Architecture* (http://www.its.dot.gov/arch/) provides general user service requirements that can be used as a starting point in developing one or more of their three market packages: ITS Data Mart, ITS Data Warehouse, and ITS Virtual Data Warehouse.
- The *Archived Data Management System Data Model* report was produced in 2002 to aid in the development of data archives (http://www.fhwa.dot.gov/policy/ohpi/travel/adus.htm). The Data Model provides several use-case diagrams that clearly define the key actors (entities that interact with the data archive system) and how they use the archived data system.
- The *ASTM 2259-03a standard, Standard Guide for Archiving and Retrieving ITS-Generated Data* (http://www.astm.org) provides basic guidelines for the development of data archives. The ASTM standard is not prescriptive in terms of system design but provides general principles and further elaboration on user requirements. Some of the material in the ASTM 2259 Standard Guide was derived from a TTI report, *Guidelines for Developing ITS Data Archiving Systems* (http://tti.tamu.edu/documents/2127-3.pdf), which also contains basic guidelines and case studies on data archives.

The summary that follows is based on materials developed in SHRP 2 Project L02, Establishing Monitoring Programs for Mobility and Travel Time Reliability, and NCHRP 3-68: Guide to Effective Freeway Performance Measurement (See NCHRP web-only document 97, August 2006).

The data for performance monitoring can be derived from two basic sources: traditional traffic studies that use sample performance data for specific times and locations, and traffic operations data collected continuously at multiple locations. Data quality, data management and fusion, and data fidelity are three important components related to performance data monitoring.

Component 1: Data Quality

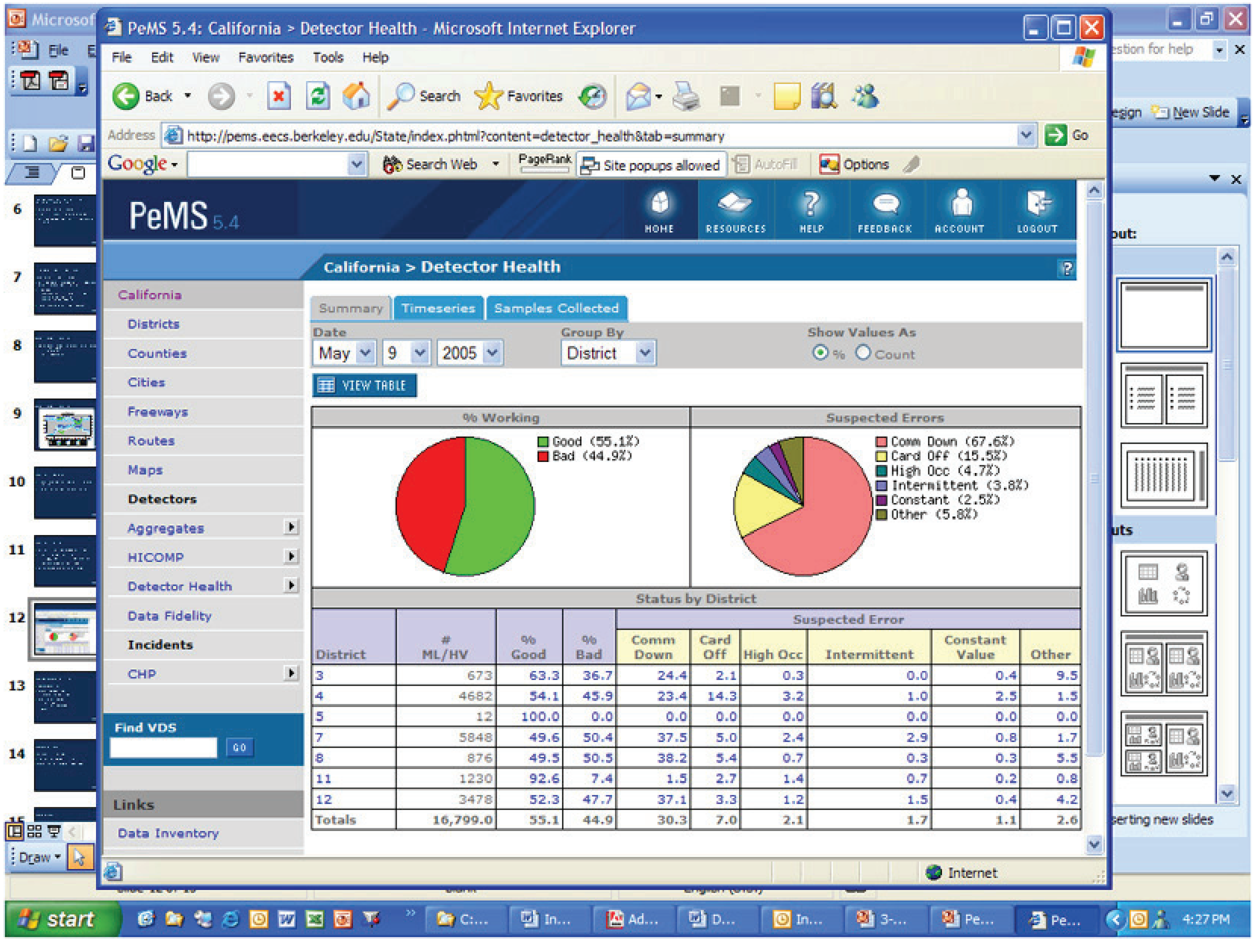
Quality assurance procedures are necessary whatever the source, but if archived data are obtained directly from traffic operations systems, the amount of data demands an automated and rigorous process.

Caltrans (California Department of Transportation) Performance Measuring System (PeMS) (*4*) contains a number of ways to view the quality of the data: by location, time, and cause of error. The PeMS screenshot in Figure 3.10 shows a pie chart with percentages of "good" and "bad" data with a second pie chart that shows the type of errors encountered for bad data. This second chart allows managers to diagnose whether the bad data have been caused by communications problems, hardware failures, or other breakdowns. Although the screenshot is for the entire state, it offers the capability to drill down from the statewide system level to specific problems that may be occurring in a single lane at a location.

Component 2: Data Management and Fusion

Data from different sources and for different performance measures need to be combined into one seamless network of databases. The four components of the management and fusion of data are metadata, data archive development, data integration, and data transformation.

- Metadata are "data about data" and typically describes the content, quality, lineage, organization, availability, and other characteristics of the data.
- Data archives can be developed in a number of ways, as discussed earlier in this chapter. A list under the subheading Available Tools and Methods names references offering further information.
- Data integration is particularly relevant when data come from more than one source. It often requires the development of a cross-reference scheme to align the data between two or more location referencing systems. In addition, version control is critical to document when changes have been made to the system that may affect performance data (e.g., new algorithms).
- Data transformation is a typical step in preparing real-time traffic data for permanent storage in a data archive whereby the original level of detail in the real-time data is reduced for storage requirements and quick access.



California > Detector Health

Date: May 9 2005
Group By: District
Show Values As: ● % ○ Count

Status by District

District	# ML/HV	% Good	% Bad	Suspected Error					
				Comm Down	Card Off	High Occ	Intermittent	Constant Value	Other
3	673	63.3	36.7	24.4	2.1	0.3	0.0	0.4	9.5
4	4682	54.1	45.9	23.4	14.3	3.2	1.0	2.5	1.5
5	12	100.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
7	5848	49.6	50.4	37.5	5.0	2.4	2.9	0.8	1.7
8	876	49.5	50.5	38.2	5.4	0.7	0.3	0.3	5.5
11	1230	92.6	7.4	1.5	2.7	1.4	0.7	0.2	0.8
12	3478	52.3	47.7	37.1	3.3	1.2	1.5	0.4	4.2
Totals	16,799.0	55.1	44.9	30.3	7.0	2.1	1.7	1.1	2.6

Figure 3.10. *Example from Caltrans PeMS website showing quality of health data.*

Component 3: Data Fidelity

Several different geographic and time scales are available for analysis and reporting. Ultimately, the intended audience will determine the geographic scale and level of detail provided in performance measure reports that could range from detailed bottleneck locations to broad regionwide reports.

Only after a robust database is developed does the reliability analysis take place. Typically, along with other performance measures, reliability is calculated using the data and displayed in the front-end user interface.

The majority of monitoring and management tools that have been developed to date function as dashboard tools that provide access and analysis capabilities to one or more underlying archived data systems. The analysis capability of any given tool is subservient to the availability, reliability and quality of the data in the underlying databases. Most of these reports are published periodically (usually weekly or monthly) on agency websites, and they report on several different operations activities that relate to reliability (e.g., freeway service patrol assists, incident duration and timeline, and traveler information data). Georgia Department of Transportation (DOT) produces a separate annual report that provides data and trend analysis on reliability statistics, including the buffer index and travel time index.

A recent trend in performance reporting and dashboard tools has been near real-time performance reporting and analysis tools developed both by private sector vendors as well as internally by some public transportation agencies. Figure 3.11 presents an example dashboard analysis application developed by the Las Vegas Regional Transportation Commission (RTC) Freeway and Arterial System of Transportation (FAST) Center. This analysis tool was developed to provide instantaneous access to real-time and historical traffic and incident data by an interactive web-based report. The tool provides a number of user-modifiable analysis capabilities of a wide range of performance measures, including travel time and buffer indices.

Each application of these tools needs to be customized and configured to the data available in the regional archived data systems and the needs of the users. The typical high-level process for development of these systems traces the following steps:

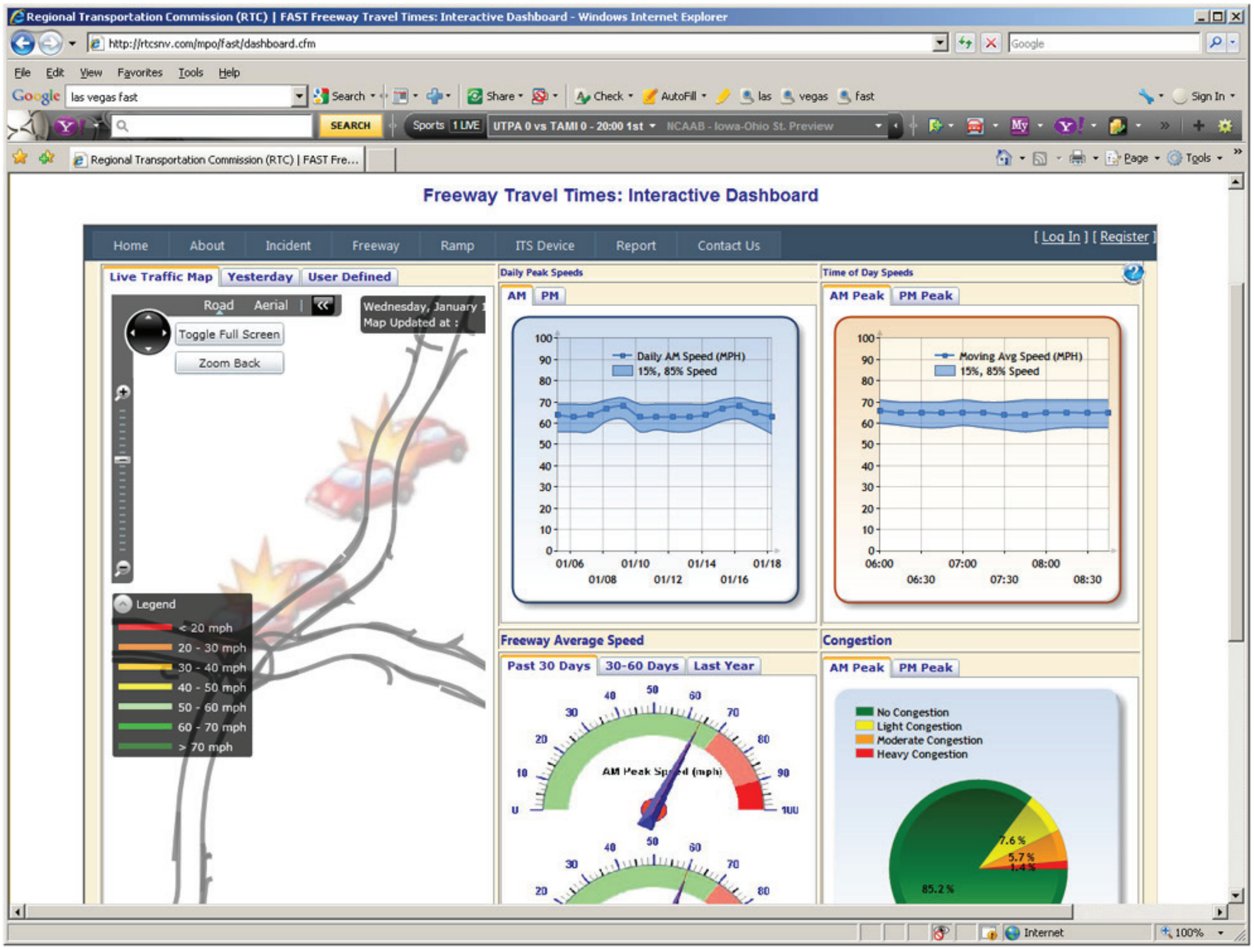


Figure 3.11. *Example of management and monitoring tools.*

1. Determine high-level user requirements for the system (who will use it, what they will use it for, etc.);
2. Assess the availability and quality of data in existing archived (or real-time) data systems;
3. Identify desirable reliability performance measures based on the needs of the agency (and associated stakeholders) and possibly based on current and future available data;
4. Determine the ability to assess identified performance measures from the available data sources;
5. Develop detailed requirements for the tool, including analysis methodologies and format of outputs (e.g., graphical comparisons);
6. Review existing similar systems and assess applicability to acquire and customize them;
7. Develop or acquire/customize and test the system using archived data;
8. Integrate the system with existing data and system maintenance plans; and
9. Monitor and manage the system.

Examples of performance reporting and analysis systems were developed for the CalTrans Performance Management System (PeMS) and a system, called OpsTrac, developed to monitor work zone traffic conditions on I-94 for the Michigan Department of Transportation (DOT).

Appropriate Situations for Applying the Tools and Methods

Monitoring and management tools themselves cannot predict future travel time reliability or the changes in reliability resulting from the implementation of programs or projects, but for a robust reliability analysis, monitoring and management tools are the best place to start. They provide a detailed understanding of the current conditions in order to develop mitigation strategies, and they provide the mechanism to track progress.

The development and application of monitoring and management tools require the availability of supporting traffic data. Essentially, the robustness of the developed system is dependent on the availability and quality of the data supporting it. Relatively simple systems can be established with very limited data, assuming that sufficient data exist to make the reliability analysis outputs meaningful. For regions with very robust traffic data archives, monitoring and management tools can make the data much more accessible to a wider range of stakeholders.

Input Data

To measure reliability empirically, continuously collected travel time data are a strict requirement. Travel time data can be obtained directly from probe data sources or derived from spot speed, volume, and occupancy data collected using infrastructure-based detectors. Detailed information on data collection methods is provided in Appendix E. Coverage and time periods for reporting should be based on project or agency priorities and the level of aggregation of the data. Reliability is most commonly applied to facility segments (because of data availability), but it can also be applied to entire trips (e.g., door to door). Ideally, facility segments should range from 2 to 5 mi in length and be based on logical breakpoints where traffic patterns change (e.g., major intersections, the central business district). Time periods for reporting could include peak hour, peak period, or daily, depending on the available level of aggregation of the data. Travel time data should be aggregated to the lowest level available, usually 1-min, 5-min, or 15-min summaries.

To support reliability monitoring data collection, agencies need to thoroughly evaluate the existing data sources in their region and determine how they can be leveraged to support travel time computations. Agencies can then determine how these sources can be integrated into the reliability monitoring system and identify where existing infrastructure should be supplemented with additional sensors, special studies, or data sources.

Output Metrics

The output metrics generated by monitoring and management tools and methods are largely determined by

- The desired output performance measures selected by the stakeholders;
- The availability of data in the region to drive the analysis; and
- The quality of the data used in the analysis.

Since most of the monitoring and management tools and methods are individually developed and configured to the available data within a region, nearly any output metric or data comparison can be customized for application within the tool, assuming the required data are available.

Integration with Larger Congestion Performance Monitoring Efforts

Reliability is an aspect of congestion; it describes the variation in day-to-day congestion for a facility or trip. Additionally, congestion has spatial aspects (how much highway space is consumed with congestion?) and temporal aspects (how long does congestion last?). Therefore, reliability performance will be a key part of an overall congestion monitoring effort, not separate from it. Other research has identified how a congestion monitoring program can be developed. In particular, additional performance measures are required to describe the spatial and temporal aspects of congestion. For example, NCHRP Report 618 identified several performance measures for this purpose, including a subset of the same reliability measures recommended in this report (Table 3.4) (*5*).

3.6 LEVERAGING OTHER SHRP 2 RELIABILITY PROJECTS AND PRODUCTS

Several other SHRP 2 research projects deal with the technical and institutional aspects of incorporating travel time reliability into agency processes. A subset of these projects deals with the measurement and estimation of travel time reliability, and several

TABLE 3.4. RECOMMENDED MEASURES FOR REPORTING TRAVEL TIME, DELAY, AND RELIABILITY FROM NCHRP REPORT 618

Recommended Performance Measures	Congestion Component Addressed	Geographic Area Addressed	Typical Units Reported
Travel Time Measures			
Travel time	Duration		Person-minutes/day, person-hours/year
Total travel time	Duration		Person- or vehicle-hours of travel/year
Accessibility	Extent, intensity	Region, subarea	Number or percent of "opportunities" (e.g., jobs) where travel time ≤ target travel time
Delay and Congestion Measures			
Delay per traveler	Intensity	Region, subarea, section, corridor	Person-minutes/day, person-hours/year
Total delay	Intensity	Region, subarea, section, corridor	Person- or vehicle-hours of delay/year
Travel Time Index or Travel Rate Index	Intensity	Region, subarea, section, corridor	Dimensionless factor that expresses ratio of travel conditions in the peak period to conditions during free-flow (e.g., TTI of 1.20 = congested trip is 20% longer than free-flow trip)
Congested travel	Extent, intensity	Region, subarea	Vehicle-miles under congested conditions
Percent of congested travel	Duration, extent, intensity	Region, subarea	Congested person-hours of travel (PHT) as % or ratio of total PHT
Congested roadway	Extent, intensity	Region, subarea	Number (or percent) of miles of congested roadway
Misery Index	Duration, intensity	Region, subarea, corridor	Proportion or percentage (e.g., 1.50) (expressing time difference between the average trip and the slowest 10% of trips)
Reliability Measures			
Buffer Index	Intensity, variability	Region, subarea, section, corridor	Percent extra time to be allowed to ensure on-time arrival (e.g., "BI of 30%")
Percent on-time arrival	Variability	Facility, corridor, system	Percent of trips meeting definition of "on time"
Planning Time Index	Intensity, variability	Region, subarea, section, corridor	Dimensionless factor applied to normal trip time (e.g., PTI of 1.20 x 15-min off-peak trip = 18-min travel time for travel planning purposes)
Percent variation	Intensity, variability	Region, subarea, section, corridor	Percent of average travel time required for on-time arrival of given trip, similar to planning time index
95th percentile	Duration, variability	Section or corridor	Trip duration in minutes and seconds

products have been developed by these projects. Appendix A presents a general summary of these projects. This section presents analysts with additional information on how the other SHRP 2 research can be incorporated into planning and programming activities (see Table 3.5).

TABLE 3.5. SHRP 2 RELIABILITY RESEARCH PROJECTS AND HOW THEY CAN BE USED IN THE PLANNING AND PROGRAMMING PROCESS

Number	Project Title	Use in Project L05 Planning and Programming Activities
SHRP 2 L01	Integrating Business Processes to Improve Reliability	Provides guidance on how internal agency structures and processes can be transformed to focus on transportation operations. Project L34 is developing an e-Tool for implementation of the L01 concepts. Training will be available for applying the e-Tool.
SHRP 2 L02	Establishing Monitoring Programs for Mobility and Travel Time Reliability	Developed guidance on how to structure a travel time reliability monitoring program. The report covers data collection technologies, performance measures, data processing methods, and data presentation. Data include not only travel time data but data required to measure the sources of congestion: incidents, weather, and work zones. In addition to the L05 performance measures, another performance measure is recommended by tracking reliability: the semi-variance. The guidance could be used to develop functional requirements for an information management system for monitoring congestion and reliability.
SHRP 2 L03	Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies	Developed most of the foundational concepts for reliability and sketch-planning-level prediction methods, which have been extended into formal tools (Projects L07 and C11).
SHRP 2 L04	Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools	Developed a framework for integrating travel demand forecasting and traffic simulation models for predicting reliability. Further testing and validation needs to be conducted before the full framework can be implemented, but the concepts are useful to agencies wishing to undertake a more microscale analysis of reliability.
SHRP 2 L06	Institutional Architectures to Advance Operational Strategies	NCHRP 3-94 refined the methods and FHWA is now sponsoring workshops based around the capability maturity model, which is an elaborate self-assessment for determining at what stage of development an agency is with regards to the key factors related to operations. Once the self-assessment is complete, the method then suggests ways for advancing in each key area. The method used in L06 has been adapted in this report—agencies are encouraged to apply it to gain an understanding of their current operations status.
SHRP 2 L07	Evaluating Cost-Effectiveness of Highway Design Features	A spreadsheet tool, based on the L03 research, has been developed for assessing the reliability impacts at the project level. The project also identified how design strategies and other forms of improvements can be analyzed with the model.
SHRP 2 L08	Incorporation of Travel Time Reliability into the *Highway Capacity Manual*	Analytical methods, based on the HCM's Freeway Facilities and Urban Streets methods, have been developed. The methods rely on developing "scenarios"—combinations of the sources of unreliable travel. Software currently exists to implement the procedure, which is a combination of a scenario generator front end to existing HCM-based software (FREEVAL and STREETVAL), but the interfaces are not yet user-friendly.
SHRP 2 L11	Evaluating Alternative Operations Strategies to Improve Travel Time Reliability	Investigated an innovative approach to valuing travel time reliability, which agencies should consider when performing cost analysis of reliability-oriented projects.
SHRP 2 L13 and SHRP 2 L13A	Archive for Reliability and Related Data	The archive houses the data from all of the Reliability projects, and agencies could access the data if they needed to develop factors or default values for analyses.

(continued)

TABLE 3.5. SHRP 2 RELIABILITY RESEARCH PROJECTS AND HOW THEY CAN BE USED IN THE PLANNING AND PROGRAMMING PROCESS (continued)

Number	Project Title	Use in Project L05 Planning and Programming Activities
SHRP 2 L14	Traveler Information and Travel Time Reliability	Undertook original research to determine how travelers perceive travel time reliability. The results are very useful for explaining technical analyses that use reliability and can be used to educate the public and decision makers when agencies are explaining such things as performance reports.
SHRP 2 L17	A Framework for Improving Travel Time Reliability	A variety of outreach and educational materials on the importance of reliability and operations strategies have been produced. As with L14, these are useful in explaining why agencies are including reliability in technical analyses and incorporating operations in their tool boxes. Additionally, L17 also undertook several small gap-filling projects that are relevant for planning and programming. These include • *Deployment Guidance for TSM&O Strategies*: provides a synthesis of current agency practices for planning short-term operational deployments. • *A Guidebook for Standard Reporting and Evaluation Procedures for TSM&O Strategies*: provides a standard procedure for conducting empirical before-and-after analyses of operations strategies. • *Guidebook: Placing a Value on Travel Time Reliability*: provides a review of the past literature on reliability valuation. • *Integration of Operations into Transportation Decision Making*: provides the decision-making structure and supporting information needed to integrate operational improvements into overall transportation, using the PlanWorks, (formerly known as TCAPP) webtool developed by SHRP 2 Project C01. This content has become part of C01.
SHRP 2 L35	Local Methods for Modeling, Economic Evaluation, Justification and Use of the Value of Travel Time Reliability in Transportation Decision Making	These are a series of case studies being conducted by agencies using many of the recommendations presented in this report. The case studies are including reliability in the benefit stream of improvements, including the valuation of reliability.
SHRP 2 L38	Pilot Testing of SHRP 2 Reliability Data and Analytical Products	Agency testing of reliability products, including L02, L05, L07, L08, and C11.
SHRP 2 C10A and B	Partnership to Develop an Integrated, Advanced Travel Demand Model and a Fine-Grained, Time-Sensitive Network	These two projects integrated activity-based travel models with mesoscopic simulation. They are currently undergoing further testing. While it is likely this work will lead to new tools, they are still experimental at this point.
SHRP 2 C11	Development of Improved Economic Analysis Tools Based on Recommendations from project C03	Developed a spreadsheet tool for doing sketch-planning-level analysis based on the procedure identified in this report. In addition to being a formal tool, the procedures from this report have been updated, so this version is the latest incarnation of the procedure. The procedure can be used as a stand-alone model for project level analysis or could be developed as a post-processor to travel demand forecasting models.

3.7 REFERENCES

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4

TOOL AND METHOD SELECTION PROCESS

This chapter provides practitioners with guidance on planning a successful reliability analysis that will meet the objectives of the planning product being developed. It includes a discussion of the various factors that influence selection of an appropriate analysis approach based on analysis needs.

Before initiating an analysis of travel time reliability, many factors need to be considered that will help to select a method and structure an approach appropriate to the needs of the analysis. This careful planning will help to ensure that the outputs ultimately fit the needs and are appropriate to the intended audience, and that the analysis can be reasonably completed within resource constraints (schedule, budget, data availability, and staff skills). Florida is a good example of this. The Florida Department of Transportation (DOT) Operations Office uses a real-time data monitoring tool, while the Planning Office uses a model post-processing tool. They meet quarterly to discuss projects and initiatives related to travel time reliability, and the Florida DOT is comparing modeled results with those based on travel time monitoring data to make refinements to their travel time reliability model (see the Florida DOT case study for more information).

The influencing factors are the basis for the five-step tool selection framework outlined in the flowchart in Figure 4.1 and explained further in this chapter (see Sections 4.1 through 4.5).

- *Step 1. Plan Reliability Analysis*. Define the role in the planning process that the analysis is intended to support or fulfill, the analysis scope, and level of detail required.

Color versions of the figures in this chapter are available online: http://www.trb.org/Main/Blurbs/168856.aspx

- *Step 2. Filter by Input Requirements*. Filter out tool and method categories based on the availability of reliable and relevant data required to support various analysis tools and methods.
- *Step 3. Identify Resource Availability*. Compare the needs of the analysis against the available agency resources (e.g., budget, schedule, staff resources, and skill levels) to ensure that the analysis may be completed as planned under these assumptions.
- *Step 4. Apply Scoring Mechanism*. A scoring mechanism is applied to Steps 1 through 3 to help guide the analyst through the tool selection process and ensure all influencing factors are considered in the decision.
- *Step 5. Review and Reality Check*. Review the outcome of the scoring process and consider the overarching objectives to make the final selection.

This chapter examines the influencing factors in more detail, providing a general framework that can be used in identifying and developing a methodology appropriate to the needs of a particular analysis. Practitioners must consider all of these factors simultaneously to identify areas of disconnect and to avoid having to complete the process in many multiple iterations. For example, if it is known from the beginning that only limited resources are available to conduct the analysis, the agency will need to make the decision early on to either curtail the overall analysis objectives or increase the level of resources available to conduct the analysis.

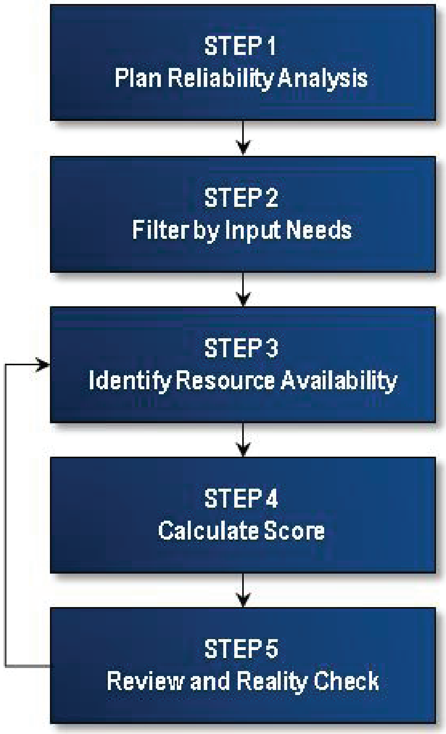

Figure 4.1. *Tool selection framework.*

The output of this process will be the identification of an analysis approach that is appropriate to the needs and objectives of the particular reliability assessment. This general approach will then be further refined and applied in the conduct of the analysis.

4.1 STEP 1. PLAN RELIABILITY ANALYSIS

It is important to consider the role in the planning process that the analysis is intended to support or fulfill. Each of the different stages of the planning process has different needs that can influence the appropriateness of the tools and methods selected to perform the reliability analysis. These general needs and the influences they place on the tool or method selected are referred to as analysis objectives. Seven analysis objectives are included in the tool selection process:

- Identify historical trends and deficiencies;
- Identify long-term needs;
- Conduct trade-off analysis;
- Prioritize needs or projects;
- Select the optimal project or alternative;
- Conduct a benefit–cost analysis; and
- Monitor and manage the system.

The analysis scope has major implications for the selection of an appropriate method. The scope is defined in terms of geographic area, analysis period, and strategies to be analyzed. The strategies are grouped by the cause of congestion that they are best suited to alleviate: capacity, operations, and demand.

The final selection criterion considered in the initial planning of the analysis is the level of detail required. The level of detail refers to the level of confidence in the accuracy of the results. Typically, analyses conducted in the earlier stages of the planning process require less accuracy but as strategies become more detailed, the analysis must also.

Even if it is already known (or guessed) which tool type will be selected, the process outlined in Step 1 can be a framework or checklist of critical items that must be considered before conducting reliability analysis.

In Table 4.1, the “●” represents when a tool or method can directly address the line item, a “⦿” when it somewhat addresses the item, and a “○” when it cannot. The analyst should review each line item in this table and identify whether each line item is relevant to the analysis at hand.

TABLE 4.1. OBJECTIVES, SCOPE, AND PERFORMANCE MEASURES OF RELIABILITY ANALYSIS TOOLS AND METHODS

Influencing Factors	Sketch-Planning Methods	Model Post-Processing Methods	Simulation or Multiresolution Methods	Monitoring and Management Tools/Methods
Analysis Objectives				
Identify Historical Trends and Deficiencies	○	○	○	●
Identify Long-Term Needs	●	◉	○	○
Conduct Trade-Off Analysis	●	●	●	○
Prioritize Needs or Projects	●	●	○	○
Select Optimal Project or Alternative	○	●	●	○
Conduct Benefit–Cost Analysis	◉	●	◉	○
Monitor and Manage System	○	○	○	●
Geographic Scope				
Regionwide	●	●	○	●
Subarea	●	●	●	●
Corridor	●	●	●	●
Isolated Location	●	○	○	●
Temporal Scope				
Daily	●	●	○	●
Peak Period	●	●	●	●
Peak Hour	●	●	●	●
Less than 1 Hour	○	○	●	●
Alternative Type				
Capacity	●	●	●	○
Operations	○	○	●	○
Demand	◉	◉	○	○
Detail of Analysis				
Level of Confidence in Accuracy	○	◉	●	●

Note: ● = can directly address the item; ◉ = somewhat addresses the item; ○ = cannot address the item.

4.2 STEP 2. FILTER BY INPUT REQUIREMENTS

The goal of Step 2 is to filter out tool and method categories based on the availability of input requirements, including data needs and existing tools. Consideration of available resources should be made early in the selection process and used to frame subsequent steps. In this step, the analyst needs to carefully assess the needs of the analysis identified in the previous steps against the mechanisms within the agency to support the analysis. Key among these considerations is the availability of the necessary capabilities to analyze the alternatives with the chosen method and the availability of reliable and relevant data to support the analysis. Without the ready provision of these items, the analysts will need to plan additional resources in order to develop the base modeling or data collection capabilities to properly support the analysis. The additional resources are likely to be far greater than the initial resources; therefore, at this stage in the selection process, it is recommended to eliminate any method that requires tools or data that are not presently available. Table 4.2 lists the tools and data sets required for each method.

For sketch-planning methods, none of the listed available tools are needed, but volumes, capacities, and segment free-flow speeds are required for the analysis. If a travel-demand model is available for model post-processing methods, it can be assumed to contain the volumes, capacities, and free-flow speeds needed for the analysis. Therefore, these data are marked “NO” under the Available Data section of Table 4.2 for this method. Similarly, if a simulation model is available for simulation methods or an archived data system is available for the monitoring and management tools/methods, the volumes, capacities, and free-flow speed data needs are also marked “NO.”

As described in Section 3.1, a fifth method category is multiscenario methods. Multiscenario analysis may be developed and applied on top of any of the four analysis methods described in Table 4.2 to provide additional assessment of reliability during nontypical conditions. If the multiscenario method is selected, additional data about the probability of nonrecurring delay are needed. If the simulation method is selected for multiscenario analysis, detailed strategy/alternative information is needed. These data needs are marked “MAYBE.” The absence of these data does not exclude either method from the selection process at this stage because assumptions can be used in their place, but it is important to note that without these data, the methods are not able to reach their full potential.

TABLE 4.2. INPUT REQUIREMENTS FOR DIFFERENT RELIABILITY ANALYSIS TOOLS AND METHODS

Tools and Data Requirements	Sketch-Planning Methods	Model Post-Processing Methods	Simulation Methods	Monitoring and Management Tools/Methods
Available Tools				
Travel Demand Model	NO	YES	YES	NO
IDAS or Similar Post-Processor	NO	YES	NO	NO
Simulation Model	NO	NO	YES	NO
Archived Data System	NO	NO	NO	YES
Available Data				
Segment Volumes	YES	NO	NO	NO
Segment Capacities	YES	NO	NO	NO
Segment Free-Flow Speeds	YES	NO	NO	NO
Probability of Nonrecurring Delay Data	NO	MAYBE	MAYBE	NO
Detailed Strategy/Alternative Information	NO	NO	MAYBE	NO

4.3 STEP 3. IDENTIFY RESOURCE AVAILABILITY

Step 3 in the analysis method selection process is to compare the needs of the analysis against the available resources to ensure that the analysis may be completed as planned under these assumptions (Table 4.3). If a severe disconnect exists between the resources needed to conduct the proposed approach and the available resources, the analysts must rethink their proposed approach and/or adjust the amount of resources.

When considering the influence resources have on selecting the appropriate tool or method, practitioners should consider resources related to several issues, including

- Budget;
- Schedule; and
- Staff resources and skill levels.

If the analyst is confident that the resources are balanced—that is, the proposed approach is weighed against available resources—the analysis tool or method is appropriate and work may proceed.

TABLE 4.3. ANALYSIS RESOURCES REQUIRED TO CONDUCT ANALYSIS

Influencing Factors	Sketch-Planning Methods	Model Post-Processing Methods	Simulation or Multiresolution Methods	Monitoring and Management Tools/Methods
Budget				
Low	●	○	○	○
Medium	●	●	○	○
High	●	●	●	●
Time				
Short	●	○	○	○
Medium	●	●	○	○
Long	●	●	●	●
Staff Skill Level				
Low	●	○	○	○
Medium	●	●	○	○
High	●	●	●	●

Note: ● = can directly address the item; ○ = cannot address the item.

4.4 STEP 4. APPLY SCORING MECHANISM

A scoring mechanism can be applied to Steps 1 through 3 to help guide the analyst through the tool selection process and ensure all influencing factors are considered in the decision. To begin the selection process, the analyst assigns a relevance weighting to each line item in the tables from previous steps that indicates its relevance to the analysis at hand. A relevance weighting of "5" is assigned if the line item is a high priority for the analysis or a "0" if it is not. The scoring process allows for flexible weighting in between (1 to 4), should the item fall under a "somewhat" category.

5 = High-priority objective;

1–4 = Medium priority objective; or

0 = Not an objective.

It is recommended that either a simple 0 or 5 be assigned as a starting point to get a quick base score. If similar high scores are found for more than one tool, the analyst can adjust the relevance weighting to help make the selection.

For convenience, each line item has already been assigned a tool rating as to whether or not it can directly be addressed by the tool or method. The rating for each tool or method was assigned as follows. The tool/method received a rating of "10" when the line item can directly be addressed by the corresponding tool/method type, a rating of "5" if it somewhat can be addressed, or a "0" if it cannot. In the tables provided in subsequent steps, the scores are represented by the following symbols so the analyst can more readily recognize the capabilities of each tool:

● = 10 = Directly addressed by corresponding tool or method type;

◉ = 5 = Somewhat addressed by corresponding tool or method type; or

○ = 0 = Not directly addressed by corresponding tool or method type.

The score is calculated using simple multiplication. The relevance weighting is multiplied by the tool rating to get a score for each line item. The score for each line item is added up to get an overall score for each tool. Templates for each score sheet are provided in the following tables.

Table 4.4 provides a template score sheet for the influencing factors in planning the reliability analysis (Step 1). To use the template, the analyst enters a relevance weighting (0–5) for each line item in the shaded column on the left side of the table and an influencing factor, and then calculates a score by multiplying the relevance weighting by the assigned tool rating for each analysis tool or method. The scores are entered in the shaded area on the right side of the table. The scores for each analysis tool or method are summed at the bottom of the table. As an example, relevance weightings and resulting scores have been entered for the first three line items of Table 4.4.

Table 4.5 provides a template for the analysis resource requirements (Step 3). To use the template, the analyst enters a relevance weighting of "5" for line items that match the available resource or a "0" if it does not. In this case, the analyst should assign a relevance weighting to only one line item under each category. For example,

TABLE 4.4. STEP 1 SCORE SHEET

Relevance Weighting (0–5)	Influencing Factors	Assigned Tool Rating				Score = (Relevance Weighting x Tool Rating)			
		Sketch-Planning	Model Post-Processing	Simulation or Multi-resolution	Monitoring and Management	Sketch-Planning	Model Post-Processing	Simulation or Multi-resolution	Monitoring and Management
	Analysis Objectives								
5	Identify Historical Trends and Deficiencies	0	0	0	10	**0**	**0**	**0**	**50**
0	Identify Long-Term Needs	10	5	0	0	**0**	**0**	**0**	**0**
5	Conduct Trade-off Analysis	10	10	10	0	**50**	**50**	**50**	**0**
	Prioritize Needs or Projects	10	10	0	0				
	Select Optimal Project or Alternative	0	10	10	0				
	Conduct Benefit–Cost Analysis	5	10	5	0				
	Monitor and Manage System	0	0	0	10				
	Geographic Scope								
	Regionwide	10	10	0	10				
	Subarea	10	10	10	10				
	Corridor	10	10	10	10				
	Isolated Location	10	0	0	10				

(continued)

TABLE 4.4. STEP 1 SCORE SHEET (continued)

Relevance Weighting (0–5)	Influencing Factors	Assigned Tool Rating				Score = (Relevance Weighting x Tool Rating)			
		Sketch-Planning	Model Post-Processing	Simulation or Multi-resolution	Monitoring and Management	Sketch-Planning	Model Post-Processing	Simulation or Multi-resolution	Monitoring and Management
	Temporal Scope								
	Daily	10	10	0	10				
	Peak Period	10	10	10	10				
	Peak Hour	10	10	10	10				
	Less than 1 Hour	0	0	10	10				
	Alternative Type								
	Capacity	10	10	10	0				
	Operations	0	0	10	0				
	Demand	5	5	0	0				
	Level of Confidence in Accuracy								
	Order of Magnitude to Highly Disaggregated	0	5	10	10				
Subtotal for Step 1									

TABLE 4.5. STEP 3 SCORE SHEET

Relevance Weighting (0 or 5)[a]	Influencing Factors	Assigned Tool Rating				Score = (Relevance Weighting x Tool Rating)			
		Rating for Sketch-Planning	Rating for Model Post-Processing	Rating for Simulation or Multi-resolution	Rating for Monitoring and Management	Sketch-Planning Relevance × Rating	Model Post-Processing Relevance × Rating	Simulation or Multi-resolution Relevance × Rating	Monitoring and Management Relevance × Rating
	Budget								
5	Low	10	0	0	0	**50**	**0**	**0**	**0**
0	Medium	10	10	0	0	**0**	**0**	**0**	**0**
0	High	10	10	10	10	**0**	**0**	**0**	**0**
	Time								
	Short	10	0	0	0				
	Medium	10	10	0	0				
	Long	10	10	10	10				
	Staff Skill Level								
	Low	10	0	0	0				
	Medium	10	10	0	0				
	High	10	10	10	10				
Subtotal for Step 3									

[a] The analyst should assign a "5" to only one of the line items (e.g., Low, Medium, High) under each influencing factor (e.g., Budget, Time, Staff Skill Level).

if the budget availability is medium, the analyst should assign a relevance of "5" to "Medium" and a relevance of "0" for both the "Low" and "High" line items under Budget. The relevance weighting is entered in the shaded column on the left side of the table, and then a score is calculated by multiplying the relevance weighting by the assigned tool rating for each analysis tool or method. The scores are entered in the shaded area on the right side of the table. The scores for each analysis tool or method are summed at the bottom of the table. As an example, relevance weightings and resulting scores have been entered for the first three line items of Table 4.5.

To calculate an overall score, the analyst filters out the analysis tools and methods for which input needs are not available (as determined in Step 2). Considering only the tool types that prevailed in Step 2, the overall score is calculated by adding the total score for each tool type from Steps 1 and 3. Table 4.6 provides the overall score sheet to tabulate the results.

The tool with the highest score is then reviewed in Step 5. In cases in which more than one tool or method category receives high scores that are close, it is a good idea to consider multiple options going into Step 5.

TABLE 4.6. STEP 4 OVERALL SCORE SHEET

Input Needs	Sketch-Planning Methods	Model Post-Processing Methods	Simulation or Multiresolution Methods	Monitoring and Management Tools/Methods
Step 1 Score (from Table 4.4)				
Step 3 Score (from Table 4.5)				
Overall Score (Step 1 + Step 3)				

4.5 STEP 5. REVIEW AND REALITY CHECK

After calculating the highest scoring tool(s) and method(s), the human element of the selection process is required. The analyst must step back and look at the big picture to review the outcome of the scoring process and the overarching objectives to make the final selection. Furthermore, many possible challenges may arise as the process of applying the tool or method moves forward. Common challenges include the availability of data in the required format, staff expertise, funding, and development time.

In cases in which the results do not make sense, a further weighting can be assigned to each of the steps to prioritize objectives that are very strict requirements (e.g., geographic or temporal scope, output performance objectives, and available resources).

For example, the highest score may result in simulation, and the desired outcome is peak period reliability. However, it is later found that the available simulation model covers only the peak hour. If financial and time resources are not available to collect what is needed and calibrate an expanded simulation model, a simpler tool should be considered.

The selection process can also be used to make an argument to increase resources or decrease the scope instead of changing the method or tool. If the resource shortfall is related to staff availability or skill levels, or to computing resources, the agency may want to consider contracting out part of the analysis to a third party with available resources (e.g., consultants, universities, research organizations, partner agencies). If the resource deficit is primarily related to budget, the agency may want to consider pooling resources with other regional agencies that may also be interested in the reliability analysis.

The reduction in scope can be achieved by

- Reducing the detail of the analysis;
- Limiting the number of alternatives by combining them into logical groups;
- Limiting the temporal analysis period by assuming the peak period reliability is representative of the peak hour, or vice versa; or
- Reducing the geographic scope to representative corridors.

Case Study: Minneapolis–Saint Paul Region Uses Representative Corridors to Estimate Regionwide Benefits of Ramp Metering

The Minneapolis–Saint Paul metropolitan region wanted to conduct a regionwide analysis on the benefits of their ramp metering system, but limited resources did not allow for detailed data collection and analysis on all corridors in the region. Instead, they selected four representative freeway corridors in the region: (1) a downtown corridor, (2) a radial corridor inside the beltway, (3) a radial corridor outside the beltway, and (4) a section of the beltway corridor. The operations benefits of metering, including reliability, were examined on these representative corridors and then expanded to represent the entire region as illustrated in Figure 4.2.

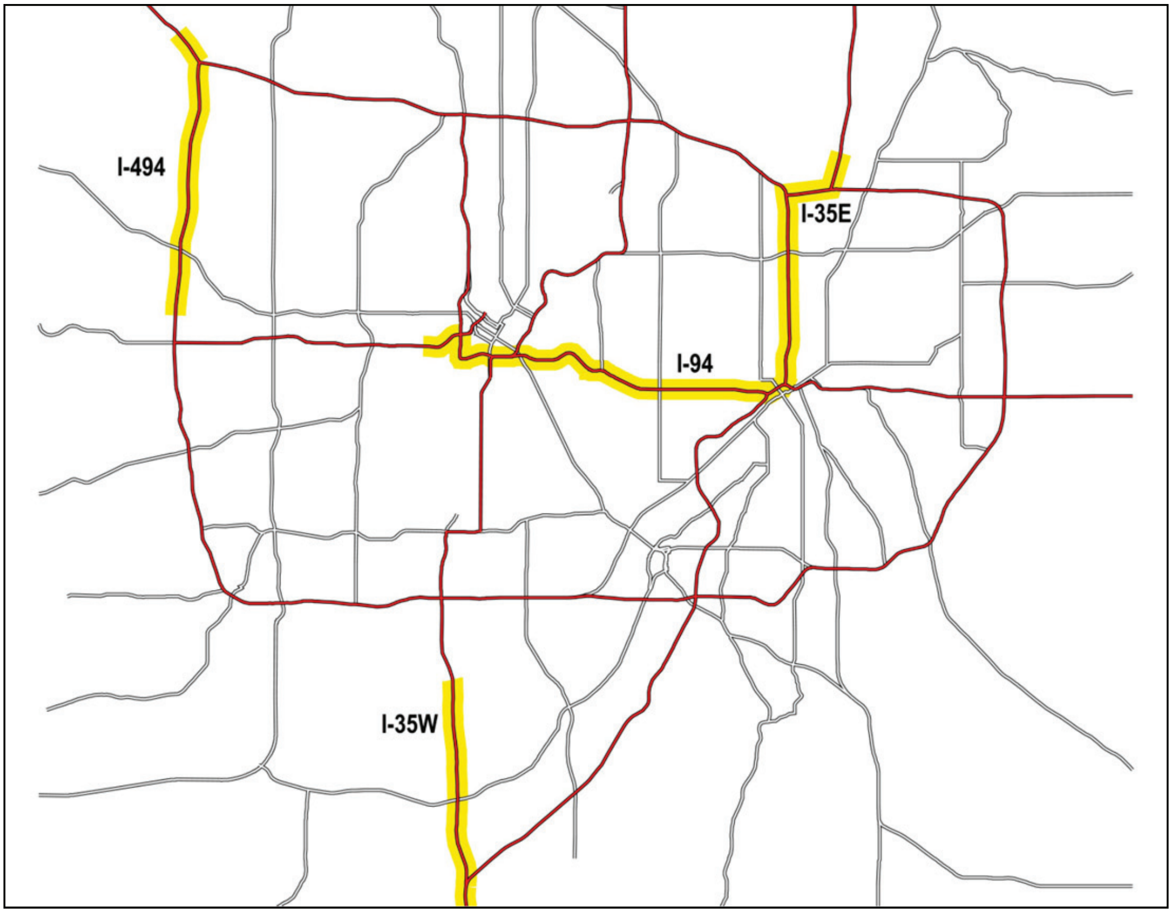

Figure 4.2. *Four representative freeway corridors in Minneapolis–Saint Paul (1).*

4.6 REFERENCE

1. *Twin Cities Ramp Meter Evaluation–Final Report*. Minnesota Department of Transportation, Saint Paul, Minnesota, 2001.

5

CONDUCTING A RELIABILITY ANALYSIS

This chapter provides a systematic approach for conducting a reliability analysis using the reliability tools and methods described in Chapter 3. Each application of these various tools and methods may vary because of differences in the purpose of the analysis, input data availability, performance characteristics of the corridor or region being analyzed, and the desired outcomes of the analysis. However, most analyses include some general steps. This chapter summarizes the general steps necessary to complete these activities. Systematic guidance is provided for

- Sketch-planning methods;
- Post-processing methods;
- Simulation and multiresolution methods;
- Monitoring and management tools and methods; and
- Multiscenario methods.

The description of the methods assumes that the reader has previously followed the process described in Chapter 4 for selecting an appropriate analysis approach and is ready to embark on the analysis. The user should have also previously established whether the analysis will include a multiscenario to enhance the method selected.

Figure 5.1 provides an overview of the general decision process taken up to this point and a mapping of remaining activities, with references to where more information on a specific process may be found in this document.

Color versions of the figures in this chapter are available online:
http://www.trb.org/Main/Blurbs/168856.aspx

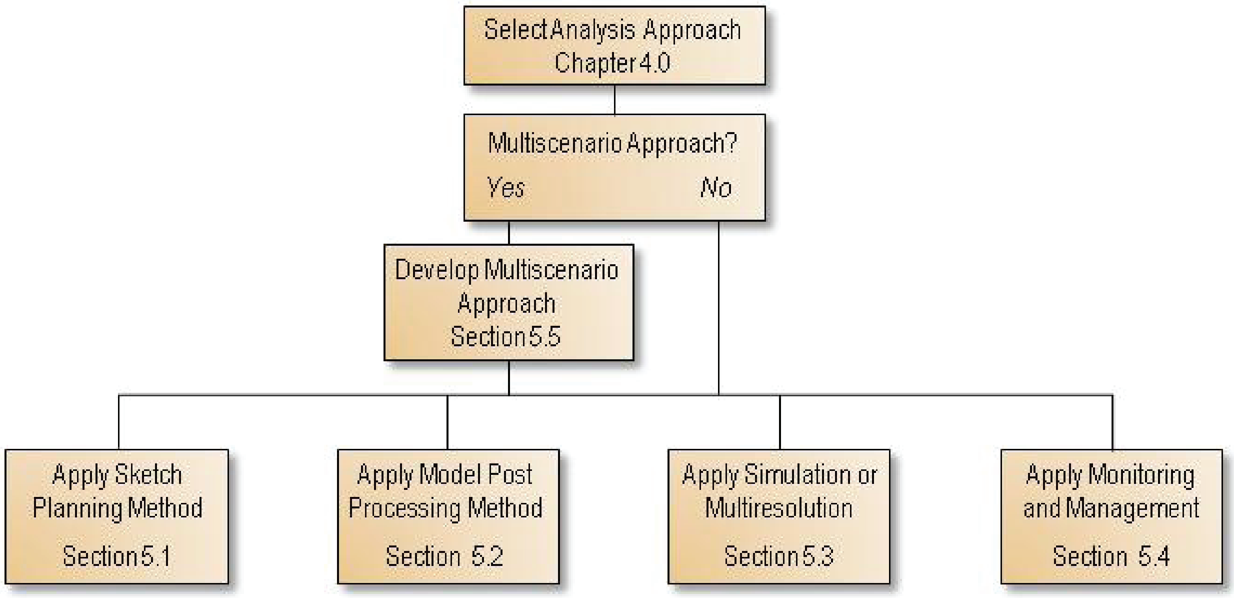

Figure 5.1. *Overview of analysis process and mapping to reference section.*

5.1 APPLYING SKETCH-PLANNING METHODS

A reliability analysis using the sketch-planning method would be expected to follow these steps.

Step 1: Confirm the Analysis Scope of Work

The temporal (e.g., peak hour, peak period) and geographic (e.g., corridor, system-wide) scope of the analysis should be confirmed to ensure that the analysis will be able to capture the anticipated reliability impacts related to all strategies being evaluated.

Step 2: Determine Analysis Segments

Once the geographic scope is confirmed, the analysts should evaluate the facilities to be covered to identify any segmentation that should occur before the gathering of data and application of the analysis. Regional networks may need to be disaggregated into logical corridors and corridors may need to be disaggregated into segments. The objective of this activity is to identify and create sections of the analysis network that represent homogeneous sections based on physical characteristics (e.g., facility type, number of lanes, surrounding land use) or operating conditions (e.g., variability of demand, peaking factors, directionality of traffic, number of incidents), or both. This step should be closely coordinated with the following step to identify data sources and compile data, as the availability and format of data may influence the identification of appropriate segments.

Step 3: Determine Appropriate Sources of Data and Compile

Data related to each of the segments defined in the previous step should then be assembled from available sources identified during the tool selection process outlined in Chapter 4. For the sketch-planning method, analysts should assemble data representing the overall mean travel time index (TTI_{mean}) for each of the individual segments in the study area. TTI_{mean} is estimated in one of two ways:

1. Using a simple relationship from the L03 research; or
2. Using a more detailed method that estimates incident delay and combines it with recurring delay.

Either method requires average travel time data, which can be recorded from the field, output from a model, or calculated using segment volume and capacity. Segment free-flow speed (FFS) is required for either method as well. The more detailed method requires the additional metric of incident delay, which can come from field data or, when not available, lookup tables provided in Appendix C.

The decision to use the simple or the more detailed method is not only based on data availability. The simple method is not sensitive to incident strategies, and therefore it should not be used when conducting alternatives analysis involving incident management strategies. Furthermore, the simple method is based on data from Atlanta, Georgia, and may not be aligned with the local conditions in the study area. It is therefore recommended to use the more detailed method when possible.

Step 4: Develop Analysis Models

Sketch-planning models are typically developed in a spreadsheet or in a simple database format for more extensive models. Using the SHRP 2 L03 approach, analysts would set up a spreadsheet to contain the identified segments and the data required to calculate TTI_{mean} based on the selected method. While developing the spreadsheet, consideration should be given to creating separate tabs for the base case and each alternative.

Figure 5.2 depicts a decision tree to guide the user through the SHRP 2 L03 methods and required data. The spreadsheet can be developed to align with the chosen path in the decision tree.

The first step is to compile free-flow speed for each segment into the spreadsheet or database. The second step is to compile average travel time data for each segment into the spreadsheet. The average travel times can come directly from field data or a model, or they can be calculated using a Bureau of Public Roads (BPR) function. During the testing of this procedure, several such functions were tested, including the function developed by Akcelik, which replicates the effect of queuing on speeds in oversaturated conditions (*1*).

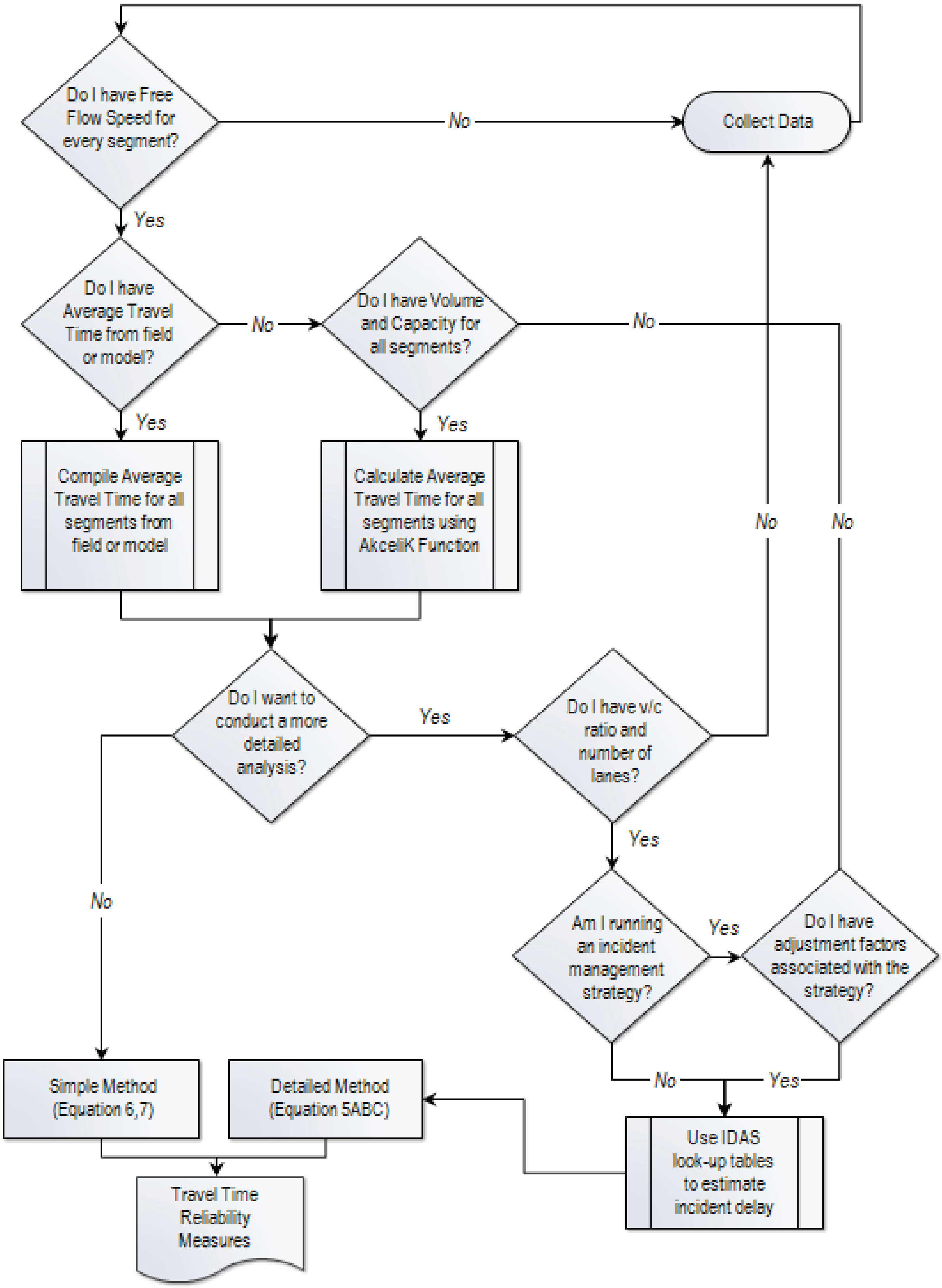

Figure 5.2. *Sketch-planning decision tree.*

$$t = t_0 + \left\{ 0.25T \left[(x-1) + \sqrt{(x-1)^2 + \frac{8J_A}{CT} x} \right] \right\} \tag{5.1}$$

where

t = average travel time per unit distance (hours/mile),

t_0 = free-flow travel time per unit distance (hours/mile) = $\frac{1}{\text{FFS}}$,

FFS = free-flow speed (miles/hour),

T = the flow period (typically 1 h) (hours),

x = the degree of saturation = volume/capacity, and

C = Capacity (vph).

$$J_A = \text{ the “Delay Parameter” } = \frac{2C}{T}(t_c - t_0)^2 \tag{5.2}$$

where t_c = the rate of travel at capacity (hours per mile).

Dowling and Alexiadis provide guidance for computing J_A for both freeways and arterials (*2*). In lieu of calculating J_A, the defaults from Akcelik may be used (Table 5.1). Although the Akcelik function may at first appear complicated, essentially only segment volumes, capacities, and free-flow speeds are needed.

TABLE 5.1. DELAY PARAMETER DEFAULT VALUES

Facility Type	J_A Value
Freeways	0.1
Arterials (interrupted)	0.2
Secondary (interrupted)	0.4

Care should be taken in applying the Akcelik function, especially to forecasts where V/C ratios can be unrealistically high. Because the remainder of the procedure is based on empirical data, with average speeds over the course of a year for a facility rarely lower than 25 mph (i.e., a mean TTI of 2.4), alternative BPR functions that do not degrade as steeply above a V/C ratio of 1.0 should be used. During testing, two such functions that produced reasonable results were identified. The first function is based on NCHRP Report 387 (*3*), and the second function is based on the work of Ruiter (*4*).

$$t = \frac{1 + 0.05x^{10}}{\text{FFS}} \quad \text{for } x < 1.0 \tag{5.3}$$

$$t = \frac{1}{50 * \left(0.55 + \left(0.444x^{-3}\right)\right)} \quad \text{for } x \geq 1.0 \tag{5.4}$$

If the simple method is selected, free-flow speed and average travel time data are sufficient to conduct the analysis. TTI_{mean} is computed using the adjustment equation from the L03 project:

$$\text{TTIm} = 1.0274 * \text{RecurringMeanTTI1.2204} \tag{5.5}$$

where

$$\text{RecurringMean\_TTI} = t/t_o \tag{5.6}$$

If the more detailed method is selected, free-flow speeds and average travel times are also required to calculate the recurring delay.

$$\text{RecurringDelay} = t - (1/\text{FFS}) \tag{5.7}$$

Incident delay is the final component needed for the calculation of TTI_{mean} in the more detailed method. Incident delay can be obtained using basic field data (i.e., segment volumes, capacities and number of lanes) and lookup tables. Lookup tables are available in the IDAS User Manual (*5*); a selection of these tables is provided in Appendix C of this document.

The recurring delay and the incident delay are then used to compute TTI_{mean} using the following equation:

$$\text{TTI}_{\text{mean}} = 1 + \text{FFS} * (\text{RecurringDelay} + \text{IncidentDelay}) \tag{5.8}$$

Because the data on which the reliability metric predictive functions are based do not include extremely high values of TTI_{mean}, it is recommended that TTI_{mean} be capped at a value of 3.0, which corresponds to an average speed of 20 mph. Even though the data included highway sections that were considered to be severely congested, an overall annual average speed of 20 mph for a peak period was never observed.

When an alternative strategy such as an incident management program involves lowering the incident rate (frequency of occurrence), then the incident delay needs to be adjusted to reflect the impact of the strategy. This can be accomplished using the following equation:

$$D_a = D_u * (1 - R_f) * (1 - R_d)^2 \tag{5.9}$$

where

D_a = Adjusted delay (hours of delay per mile),

D_u = Unadjusted (base) delay from the IDAS incident delay lookup tables (hours of delay per mile),

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, crashes are only about 20% of total incidents. Therefore, a 30% reduction in crash rates alone would reduce overall incident rates by 0.30 × 0.20 = 0.06.

After TTI_{mean} has been calculated for each segment, the reliability measures can be computed, as outlined in the following step.

Step 5: Conduct Analysis

Either of the above sketch-planning methods results in a value of TTI_{mean} for the base case and alternatives. TTI_{mean} is used to compute reliability metrics including the Planning Time Index (PTI), Buffer Index (BI), 90th percentile travel time index (TTI_{90}), 80th percentile travel time index (TTI_{80}), and standard deviation for the travel time index (StdDevTTI) as follows:

$$\text{Planning Time Index} = TTI_{95} = 1 + 3.6700 * \ln(TTI_{mean}) \qquad (5.10)$$

$$\text{Buffer Index} = (TTI_{95} - TTI_{mean})/TTI_{mean} \qquad (5.11)$$

$$\text{90th percentile TTI} = 1 + 2.7809 * \ln(\text{MeanTTI}) \qquad (5.12)$$

$$\text{80th percentile TTI} = 1 + 2.1406 * \ln(\text{MeanTTI}) \qquad (5.13)$$

$$\text{StdDevTTI} = 0.71 * (\text{MeanTTI} - 1)^{0.56} \qquad (5.14)$$

Also, the percentage of trips that are considered to be "on time" at average facility speeds of 50, 45, and 30 mph may also be computed (e.g., the percentage of trips with average facility speeds of 50 mph or greater):

$$\text{PctTripsOnTime50mph} = e^{(-2.0570*(\text{MeanTTI} - 1))} \qquad (5.15)$$

$$\text{PctTripsOnTime45mph} = e^{(-1.5115*(\text{MeanTTI} - 1))} \qquad (5.16)$$

$$\text{PctTripsOnTime30mph} = 0.333 + [0.672/(1 + e^{(5.0366 *(\text{MeanTTI} - 1.8256))})] \qquad (5.17)$$

In addition to the reliability metrics presented here, it might be necessary to monetize reliability for each alternative. The valuation approach is provided in Chapter 6.

Step 6: Review Results

As with any analysis, the results should first be thoroughly quality checked and revised according to any errors found. The results should then be documented for review and decision making.

To support the case studies of the Knoxville Transportation Planning Organization (TPO), SEMCOG [Detroit's metropolitan planning organization (MPO)], and the Washington State Department of Transportation (DOT), SHRP 2 L05 produced spreadsheets that operationalize the data-poor equations from SHRP 2 L03. The spreadsheets require the users to input capacity, volume, and length of segment and use IDAS lookup tables in conjunction with the SHRP 2 L03 data-poor equations to produce several measures of reliability, including the mean TTI, 50th percentile TTI, 80th percentile TTI, and 95th percentile TTI/PTI. It also produces a measure of overall delay that includes nonrecurring delay using the relationship of the economic value of average delay to nonrecurring delay.

Case Study: Knoxville Transportation Planning Organization (TPO) Applies Sketch-Planning Methods to Assess Reliability Impacts of Regional Intelligent Transportation System (ITS) Architecture Projects

The Knoxville TPO wanted to estimate the impacts of selected operations investments identified in its Regional ITS Architecture Update. The update to the Regional ITS Architecture was just beginning, so the TPO staff had limited input data consisting of a project list along with segment volumes, capacities, and free flow speeds. They decided to conduct a quick order-of-magnitude assessment of the reliability impacts of projects using the sketch-planning methods and the data-poor reliability prediction equations from SHRP 2 L03. Their objective was to obtain an estimate of total delay (recurring plus nonrecurring) in order to compare congestion levels with and without the investments in place. Only those projects for which quantified relationships between the investment strategy and the required inputs to the method exist (e.g., volume, capacity, free flow speed) were analyzed.

To establish baseline conditions, they applied the sketch-planning decision tree using the following steps and equations from the technical reference. First, they established analysis segments based on the geographic limits for each project and gathered relevant traffic forecast data for each segment, including year 2034 peak hour volume, capacity, number of lanes, and free-flow speed. The input data for each analysis segment were compiled into a spreadsheet, as shown in Table 5.2.

TABLE 5.2. KNOXVILLE TPO SKETCH MODEL INPUT DATA EXCERPT

Segment	Study Period	Input Data						
		Segment Type	Number of Lanes	Free Flow Speed (mph)	Percent Green	Capacity (vph)	VMT (miles)	Peak Hour Volume
Segment 1	1	Freeway	2	65	0	4,145	200,585	3,125
Segment 2	1	Freeway	2	65	0	4,145	228,505	4,689
Segment 3	1	Freeway	2	65	0	6,495	845,083	7,297

They did not have average travel time data, so they applied alternative BPR functions (Equations 5.3 and 5.4) to calculate average travel time during the peak period for each segment. For example, average travel time for Segment 1 of the Smartway Expansion Project (an uncongested freeway segment with V/C less than 1) was calculated as follows (from Equation 5.3):

$$t = \frac{1+0.2x^{10}}{\text{FFS}} = \frac{1+0.2\left(\frac{3125}{4145}\right)^{10}}{65} = 0.0156 \text{ hours/mile}$$

Average travel time for Segment 2 (a congested freeway segment with V/C greater than 1) was calculated as follows (from Equation 5.4):

$$t = \frac{1}{50 * \left(0.55 + \left(0.444x^{-3}\right)\right)} = \frac{1}{50 * \left(0.55 + \left(0.444\left(\frac{4689}{4145}\right)^{-3}\right)\right)} = 0.0234 \text{ hours/mile}$$

The equations were adapted slightly to calculate average travel time for arterial segments:

$$t = \frac{1+0.05x^{10}}{\text{FFS}} \quad \text{for } x < 1$$

$$t = \frac{1}{45 * \left(0.55 + \left(0.444x^{-3}\right)\right)} \quad \text{for } x \geq 1$$

Recurring delay was calculated for each segment using Equation 5.7. For example, recurring delay for Segment 1 was calculated as follows:

$$\text{RecurringDelay} = t - \frac{1}{\text{FFS}} = 0.0156 - \frac{1}{65} = 0.0002 \text{ hours/VMT}$$

Delay caused by incidents (D_u) was calculated using basic input data (i.e., segment volumes, capacities, and number of lanes) and the lookup tables from the IDAS User Manual. The IDAS method requires that V/C be capped at 1. For Segment 1 (V/C = 0.754, 2 lanes, 1-hour study period), the corresponding incident delay is 0.00151 hours/VMT.

The overall mean travel time index (TTI_{mean}) for the baseline condition was calculated using Equation 5.8. For example, the TTI_{mean} for Segment 1 was calculated as follows:

$$\text{TTI}_{\text{mean}} = 1 + \text{FFS} * (\text{RecurringDelay} + D_u) = 1 + 65 * (0.0002 + 0.0015) = 1.109$$

They used the TTI_{mean} to compute the Planning Time Index (PTI) and the 80th percentile TTI (TTI_{80}) using Equations 5.10 and 5.13. For example, for Segment 1:

$$\text{PTI} = 1 + 3.67 * \ln(\text{TTI}_{\text{mean}}) = 1 + 3.67 * \ln(1.109) = 1.3812$$

$$\text{TTI}_{80} = 1 + 2.1406 * \ln(\text{TTI}_{\text{mean}}) = 1 + 2.1406 * \ln(1.109) = 1.2223$$

An excerpt of results for the baseline condition is provided in Table 5.3.

TABLE 5.3. KNOXVILLE TPO SKETCH MODEL BASELINE CONDITIONS EXCERPT

	Baseline Speed and Delay Estimates						Baseline Reliability Measures		
Segment	Volume/ Capacity for Speed (V/C)	Speed	Travel Rate (TR)	Revised V/C for Incident Delay	Recurring Delay (hours/ VMT)	Incident Delay (D_u) (hours/ VMT)	TTI_m	TTI_{80}	PTI
Segment 1	0.7540	64.24	0.0156	0.7540	0.0002	0.0015	1.109	1.2223	1.3812
Segment 2	1.1314	42.69	0.0234	1.0000	0.0080	0.0199	2.816	3.2158	4.7990
Segment 3	1.1234	43.02	0.0232	1.0000	0.0079	0.0199	2.804	3.2071	4.7840

To assess improved conditions, Knoxville TPO first identified the assumed impacts of the improvement strategies in terms of decreased incident frequency, incident duration, and delay. These are summarized in Table 5.4.

TABLE 5.4. KNOXVILLE TPO SKETCH MODEL STRATEGY IMPACT ASSUMPTIONS

Strategy	Assumed Impacts
Smartway expansion	Incident duration decreased by 30%
Incident management and freeway service patrol (corridorwide)	Incident duration decreased by 30%
Ramp metering (corridorwide)	Capacity increased by 8%
Traffic signal system upgrades	Capacity increased by 8%
DMS deployment	Number of incidents decreased by 2%
CCTV camera deployment	Incident duration decreased by 4.5%
Adaptive signal system	Capacity increased by 12%

They estimated the increased capacity of the segments affected by the projects. For example, for a project that increased capacity by 8%, the increased capacity would be calculated as Capacity * 1.08. They calculated an adjusted average travel time and recurring delay for each project segment using the adjusted V/C ratios.

Since the proposed corridor reliability strategies include incident management and other strategies that lower the incident rate (frequency of occurrence), the adjusted incident delay (D_a) was calculated using Equation 5.9. For example, adjusted incident delay for Segment 1 of the Smartway Expansion was calculated as:

$$D_a = D_u * (1 - R_f) * (1 - R_d)^2 = 0.0015 * (1 - 0.3)^2 = 0.0007 \text{ hours/VMT}$$

They used the adjusted recurring delay and incident delay values to calculate the TTI_{mean}, PTI, and TTI_{80} using data-poor reliability prediction equations. The results provide an indication of future reliability with the project in place. An excerpt of results for the improved condition is provided in Table 5.5.

They used the sketch-planning results to make a relative comparison of congestion levels with the different improvement strategies in place. The results were used to identify the ITS Architecture projects that yielded the highest benefits in terms of improved

TABLE 5.5. KNOXVILLE TPO SKETCH MODEL IMPROVED CONDITION EXCERPT

Segment	Increased V/C for Speed	Improved Speed and Delay Estimates				Reliability Measures		
		Speed	TR	Incident Delay (D_a) (hours per VMT)	Recurring Delay (hours per VMT)	TTI_m	TTI_{80}	PTI
Segment 1	0.7540	64.24	0.0156	0.0007	0.0002	1.060	1.124	1.213
Segment 2	1.1314	42.69	0.0234	0.0097	0.0080	2.156	2.645	3.820
Segment 3	1.1234	43.02	0.0232	0.0097	0.0079	2.145	2.633	3.800

reliability. Knoxville TPO plans to use the analysis of benefits of selected ITS projects as input for updating the ITS Architecture for the region, and it is seen as a precursor to analysis that will be undertaken to assess operations projects proposed for the Long Range Transportation Plan (LRTP). The case study was successful in demonstrating how agencies can use sketch-planning methods to assess the reliability benefits for operations strategies within a Regional ITS Architecture and then build a roster of operations projects for inclusion in the LRTP.

Case Study: Washington State DOT Applies Sketch-Planning Methods to Identify Reliability Deficiencies and Assess Impacts of a Package of Operations Strategies

Washington State DOT wanted to identify reliability deficiencies and opportunities for improvements along a key stretch of the I-5 corridor near the Joint Base Lewis McChord military base south of Tacoma. The staff considered available data and models (regional travel demand model, observed travel times, and simulation model output), analysis resources (time, money, and staff), and desired accuracy and confidence in the results of the analysis, and decided that they would apply sketch-planning methods to estimate reliability deficiencies in the corridor. Their objective was to obtain a baseline estimate of corridor reliability and conduct an initial screening of the impacts of implementing a package of reliability mitigation measures.

To assess baseline conditions, they subdivided the corridor into three homogeneous subcorridor segments and examined each direction separately. The regional travel demand model was used to obtain input data for the subsegments, including number of lanes, peak period (3-h) volume, free flow speed, congested speed, capacity, and vehicle-miles traveled (VMT). Washington State DOT staff estimated the mean TTI by building a spreadsheet tool using the sketch-planning methods described in Section 5.1 of the technical reference. The mean TTI was calculated based on free flow speed, recurring delay, and incident delay. Recurring delay was measured as the difference between free flow travel time and actual travel time, multiplied by the volume. Incident delay was estimated using IDAS lookup tables based on number of lanes, length of the peak period, and volume-to-capacity ratio. Washington State DOT rolled up the subsegment reliability results into a corridorwide measure by calculating a weighted average mean TTI and PTI based on VMT. An excerpt of results for the baseline condition is provided in Table 5.6.

TABLE 5.6. WASHINGTON STATE DOT SKETCH MODEL BASELINE CONDITIONS

	Baseline Speed and Delay Estimates						Baseline Reliability Measures	
Segment	V/C for Speed = (V/C)	Speed	Travel Rate (TR)	V/C for Incident Delay = (V/C * Study Period)	Recurring Delay (hours)	Incident Delay (D_u) (hours)	TTI$_m$	PTI
NB from 123 to 128	0.8929	47	0.0213	2.6786	518.6	621.6	1.61	2.74
NB from 119 to 123	0.9577	47	0.0213	2.8730	333.8	1005.3	2.11	3.74
NB from 114 to 119	0.8942	54	0.0185	2.6825	187.8	710.8	1.53	2.56
SB from 114 to 119	0.6944	47	0.0213	2.0833	403.4	56.6	1.32	2.01
SB from 119 to 123	0.8942	47	0.0213	2.6825	311.6	473.8	1.70	2.94
SB from 123 to 128	0.8413	54	0.0185	2.5238	176.7	360.4	1.34	2.07
Corridor Total					**1,931.8**	**3,228.5**	**1.58**	**2.63**

Washington State DOT examined the mean TTI results to identify reliability deficiencies along the corridor. Based on knowledge gained of reliability performance measures in the state, the SHRP 2 L05 team applied professional judgment to set an initial mean TTI threshold of 1.5 to represent “unreliable” conditions. By these standards, the baseline results indicate that every northbound segment and southbound segment 2 are unreliable and need improvement. In addition, the corridor as a whole is unreliable.

Washington State DOT had completed previous work to develop a package of operations and capital strategies to improve corridor reliability. These enhancements included incident management, ramp metering, auxiliary lanes, traffic surveillance, and traveler information strategies. The staff identified the assumed impacts of these strategies by reviewing factors developed for the SHRP 2 L07 project and IDAS tool default assumptions and by adjusting them for local conditions. These are summarized in Table 5.7.

TABLE 5.7. WASHINGTON STATE DOT SKETCH MODEL STRATEGY IMPACT ASSUMPTIONS

Strategy	Assumed Impacts
Incident management and freeway service patrol (corridorwide)	Incident duration decreased by 25%
Ramp metering (corridorwide)	Freeway capacity increased by 10%, crashes reduced by 10%
Traveler information dynamic message signs (selected upstream locations)	Volume reduced by 3% (due to diversion)
Auxiliary lanes (selected locations)	Freeway capacity increased (dependent on configuration of lane), crashes reduced by 5%
Traffic surveillance cameras (corridorwide), and enhanced traffic detection (corridorwide).	No inherent impacts of deployment by themselves; however, these strategies support the other strategies and contribute to their impact.

Washington State DOT used Equation 5.9 from this technical reference to estimate the impact of reduced incident duration and reduced crashes. Decreases in volume and increases in capacity and speed were used to estimate benefits directly. The staff used the data-poor reliability prediction equations to predict the mean travel time index (TTI_{mean}) and planning time index (PTI) with the projects in place. An excerpt of results for the improved condition is provided in Table 5.8.

The analysis showed that a relatively low-cost set of improvements could improve travel time reliability in the corridor. The travel time index for the corridor with the combination of improvements deployed was estimated at 1.3, which represents a nearly 20% reduction in the index and a significant improvement in reliability. As such, these investments can be considered needs in this corridor. The case study was successful in demonstrating how agencies can use sketch-planning methods to assess the reliability impacts for a package of operations strategies within a corridor and then advance these projects in the long-range transportation plan (LRTP).

TABLE 5.8. WASHINGTON STATE DOT SKETCH MODEL BASELINE CONDITIONS

Segment	Improved Speed and Delay Estimates				Improved Reliability Measures	
	Adjusted Speed	Adjusted Travel Rate = (1/Speed)	Adjusted Recurring Delay (hours) = (t–(1/FFS))*VMT	Adjusted Incident Delay (D_a) (hours)	TTI_m	PTI
NB from 123 to 128	55	0.0182	165.3	339.2	1.277	1.899
NB from 119 to 123	54	0.0185	130.1	548.5	1.580	2.678
NB from 114 to 119	56	0.0179	117.1	387.8	1.308	1.985
SB from 114 to 119	52	0.0192	217.6	30.9	1.176	1.594
SB from 119 to 123	55	0.0182	99.4	258.5	1.327	2.040
SB from 123 to 128	56	0.0179	110.2	196.6	1.199	1.666
Corridor Total			**839.6**	**1,761.5**	**1.30**	**1.95**

5.2 APPLYING POST-PROCESSING METHODS

Model post-processing methods rely on the use of a traditional travel demand model. The SHRP 2 C05 report *Understanding the Contribution of Operations, Technology, and Design to Meeting Highway Capacity Needs* documents four key characteristics of traditional travel demand forecasting models that make them challenging to use for measuring impacts of operational improvements:

- They assume that all drivers have perfect knowledge regarding the travel time on each of the travel paths available to them.
- They assume the capacity of a freeway link or an arterial segment is a constant value while an emerging body of research indicates that such capacity is better represented as a random variable.

- They are not usually sensitive to the effects that upstream bottlenecks and blockages can have on downstream service rates.
- They implicitly assume that all vehicle trips identified within the origin–destination matrix will be completed by the end of the time period being analyzed, regardless of whether there is actually sufficient capacity to accommodate these vehicle trips within the specified time window.

Some traffic modeling advancements that begin to address these issues are under development, but they have not yet reached the point of practical and regular application. In the meanwhile, IDAS and other post-processing methods are effective ways of working around these challenges to capture the potential reliability impacts of operational improvements. The application of these methods is provided in this section.

A reliability analysis using the post-processing method would be expected to follow the following steps. Two options are described under Step 3: Option 1, a method using the IDAS application, and Option 2, a method using a customized approach directly linked to the regional travel demand model structure.

Step 1: Confirm the Geographic Scope of Analysis

The initial geographic scope of the analysis should have been identified during the initial method selection process described in Chapter 4, as the desired geographic scope has a significant influence on the appropriateness of the analysis method selected. The geographic scope should again be compared with the coverage of the regional travel demand model data to confirm sufficient coverage.

Step 2: Configure Travel Demand Model and Obtain Data

The analyst will need to determine what analysis periods (e.g., peak hour, peak period, daily) and forecast years are available to support the analysis. In addition, in larger regions and models, the analyst should evaluate any subarea models that may be available and are able to support the analysis, as this will limit the amount of model data that need to be run and analyzed. In some circumstances, various forecast years, analysis periods, or subarea models may need to be developed for use in post-processing methods. For example, the IDAS tool is limited to the input of about 14,000 individual links. If a regional model has more links than this threshold, a subarea model will need to be developed and/or used.

Step 3: Configure and Conduct Analysis

The next step depends on whether the analyst chooses to use the IDAS application directly or chooses to develop a customized subroutine based on the IDAS analysis method, as described in the following.

1. Option 1: Apply IDAS
    a. Configure data and input into IDAS: Model data including network link data and demand (trip) data are exchanged between the regional travel demand model and the IDAS application through large text (ASCII) files. Although IDAS is designed to accept data from a wide range of commonly used travel demand modeling packages, some editing and/or modification of the data may

need to occur in an interim step to ensure the data are input in the specified format (e.g., capacity values must represent per lane capacities over the selected analysis period). Please visit the *IDAS User's Manual* provided with the tool or download the manual from http://idas.camsys.com/documentation.htm for format reference and instruction on inputting the data.

b. Validate IDAS model: Before running the analysis, the IDAS model needs to be checked and validated against the regional travel demand outputs. IDAS maintains its own traffic assignment routine, and the analyst must ensure that the IDAS model is producing outputs that are a reasonable approximation of the calibrated regional travel demand model. Standard output performance measures such as vehicle-miles traveled (VMT), speeds, and number of trips should be compared between IDAS and the regional travel model. Large discrepancies may indicate that the input data were not formatted correctly, or that more assignment parameters from the regional travel model (e.g., customized speed-flow curves) need to be recreated in the IDAS model to produce results that are more accurate. This validation process is often one of the most time-consuming steps in this approach, but it is critical to the success of the analysis. See the "User Tips" section of the IDAS website for more information on validating the application.

c. Run alternatives: Once the model data are input and the results validated, the analyst may run different alternatives through the IDAS analysis process. If the alternative includes assessing strategies involving capacity or trip demand changes, these improvements should first be run through the travel demand model to assess these impacts and then run through the IDAS model to assess the level of incident-related delay. If the alternative involves ITS or operational strategies, the IDAS model has the internal capability of analyzing the impacts for many of those strategies. Figure 5.3 presents a view of the breakout of various alternatives to be analyzed in a hypothetical IDAS analysis. Alternatives A, B, and C are primarily capacity-affecting and demand-affecting strategies and would all be analyzed in the travel demand model first. The outputs from these model runs would then be input into the IDAS model and run through that model's analysis routine to estimate the incident-related delay associated with the individual control alternative and transportation system management and operations (TSM&O) options.

d. It is important to note that weather and construction scenarios are considered capacity scenarios and need to be run in the demand model. In this regard, if weather and construction management systems are to be analyzed or if weather and/or construction delay is important to the analysis, a multiscenario approach is needed.

e. It is difficult to quantify the capacity reductions associated with weather events and, although construction lane closures can be coded directly into a demand model, additional capacity reduction is expected in the neighboring lanes, which can be difficult to quantify. Two initiatives have made significant

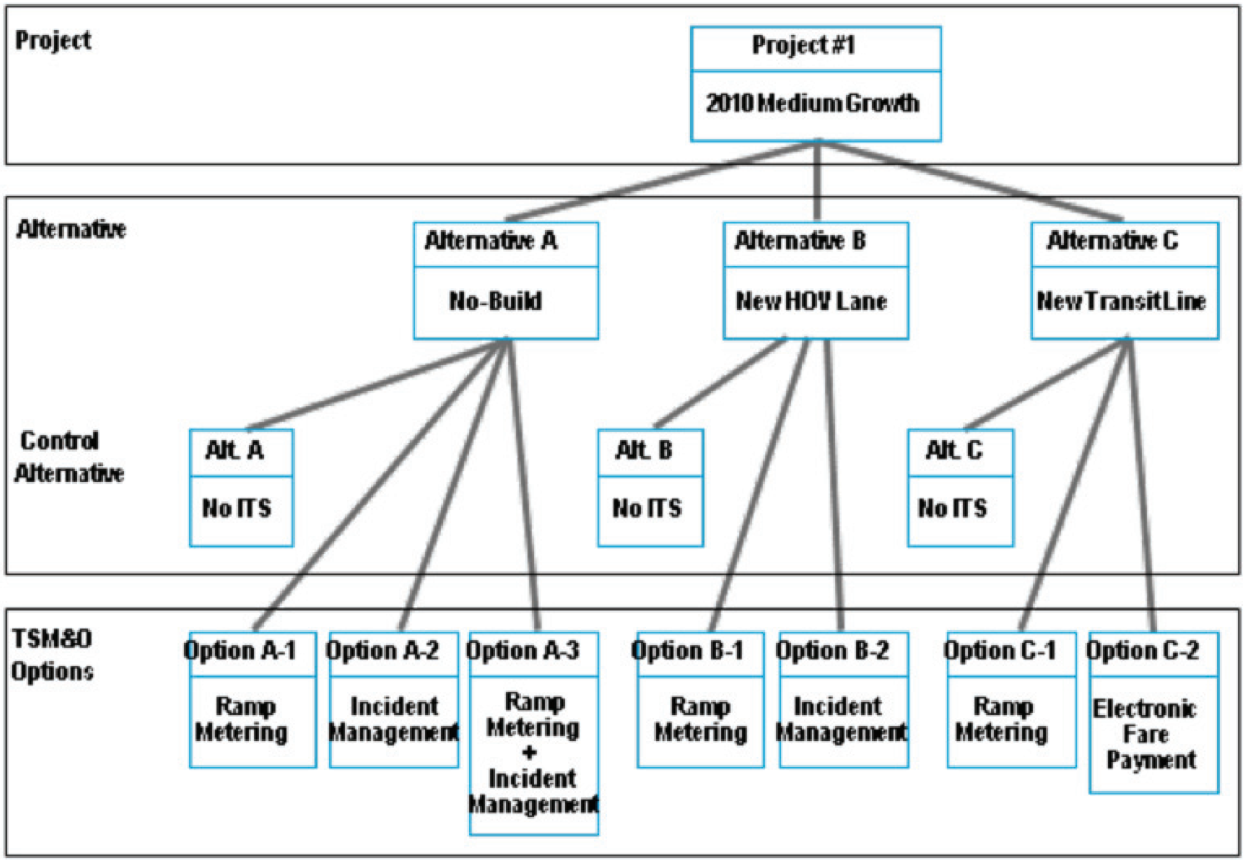

Figure 5.3. *Mapping of strategies to analysis scenarios and tools (6).*

advances in overcoming the challenges related to identifying and quantifying nonrecurring congestion and the impacts of strategies in mitigating the negative impacts. These initiatives and their findings, discussed in Section 5.5, are useful when adjusting the demand model to represent capacity reductions associated with weather and construction events.

f. Additionally, the multiscenario method requires an analysis to determine the probability of occurrence for each scenario; e.g., how many days per year have rain events but no construction events. Additional information on the execution of a probability of occurrence study is presented in Appendix D and Appendix F. The best source of this data is a monitoring and management tool discussed throughout this document.

g. After the scenarios are developed and the probability of occurrence is known, each scenario must be run in the demand model and in IDAS; the results of all the scenarios are then combined using their respective probabilities.

2. Option 2: Develop Customized Routines

In this option, the analysis methods used in the IDAS model are replicated in customized post-processing routines developed specifically to work with data from the agency's regional travel demand model.

This option may require more upfront effort to develop, configure, and test the customized routines, but this option may provide more seamless analysis later in the study, since it avoids the tedious exchange of data between the travel demand model and the IDAS application. The extra development effort may be particularly justified in analyses that will require a large number of alternatives to be analyzed or in situations where the analysis will need to be repeated in future assessments. This option is currently being used in Florida, where, although not every freeway corridor has ITS infrastructure to monitor reliability, continuous assessments of reliability are desired for all corridors (see the Florida DOT case study). The following steps are required of this option:

a. Configure analysis routines: In this step, the analysts will develop a customized routine to generate estimates of incident-related delay based on data obtained directly from the regional travel demand model. These configured applications or routines may be developed directly within the travel demand model package (depending on the capabilities provided) or in a separate post-processing step using a data analysis package (e.g., SAS). For simple, small area networks, a customized analysis routine may even be developed in a spreadsheet. The customized routine must apply a lookup function to determine an appropriate incident-related delay value to apply (based on segment or link VMT), dependent on the number of lanes and volume-to-capacity ratio of the specific link or segment. The lookup function would return the appropriate incident delay factor from the table (shown as Table 5.2 for a 1-h peak period and in Appendix C for other peak period durations). The incident-related delay value would then be multiplied with the individual link VMT and summed across all freeway links/segments in the network. (The incident-related delay analysis is limited only to freeway facilities.)

b. Test and apply routines: Following the development of the customized routines, the analysis outputs should be carefully scrutinized to ensure the reasonableness of the results.

c. Run alternatives: Once the initial results have been assessed for reasonableness, additional alternatives, representing different strategies, time-of-day, forecast years, and so forth, may be run in the analysis.

Step 4: Output and Analyze Results

Once the alternatives have been run, the results may be output for additional analysis, comparison with other alternatives, creation of graphics, and documentation.

5.3 APPLYING SIMULATION METHODS

The application of simulation methods presents some significant challenges due to the complexity of the modeling tools and the detailed nature of the analysis. The high-level steps typically required to conduct the analysis are summarized in this section. It is assumed that a calibrated simulation model is available that would meet the requirements of the reliability analysis. If a simulation model is not available and needs to be created, the analysis requires significantly more effort, expertise, and time. Guidance on the development and calibration of simulation models can be found in FHWA's *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software*.

Unlike traditional travel demand models, simulation models are more realistic in that they account for the fact that all vehicle trips identified within the origin–destination matrix may not be completed by the end of the analysis time period, because of congestion. Simulation-based dynamic traffic assignment (DTA) models, whether macro, meso, or micro, can provide an even more realistic assignment in oversaturated networks. DTA models recognize that drivers have varying levels of knowledge about the travel time on each of the travel paths available to them. As a result, they are well suited for capturing the impacts of nonrecurring congestion (such as work zones, inclement weather, and so forth) in conjunction with the operational strategies designed to address that congestion. However, DTA modeling is a complex and emerging method that is not yet widely used. A traffic analysis toolbox guidebook on DTA modeling is currently under development by the FHWA.

Under SHRP 2 project C05, Understanding the Contribution of Operations, Technology, and Design to Meeting Highway Capacity Needs, 25 capacity-enhancing operational, design, and technological strategies were identified for use on freeways, arterials, or both. Enhancements to existing mesoscopic DTA models were developed to increase the realism and the sensitivity of the models in simulating the effects of one or more strategies. More information on these enhancements and their application can be found in the SHRP 2 C05 report.

Additionally, multiscenario and multiresolution approaches are often, but not always, used in concert with simulation methods. Section 5.5 provides additional detail on the development of scenarios required in the multiscenario method. The *Integrated Corridor Management (ICM) Analysis, Modeling and Simulation (AMS) Guide*, developed by the FHWA Office of Operations, provides additional detail and guidance on the application of a multiresolution/multiscenario approach for complex analysis applications.

A reliability analysis using the simulation method would be expected to follow these steps.

Step 1: Confirm the Scope of the Analysis

The temporal (e.g., peak hour, peak period) and geographic (e.g., corridor, systemwide) scope of the analysis should be confirmed to ensure that the analysis will be able to capture the anticipated reliability impacts related to all strategies being evaluated.

Step 2: Confirm Availability of the Model Data

The temporal and geographic scope used in a simulation approach are often confined by the limits of the simulation model. If the simulation model does not encompass the entire analysis area or analysis periods, as defined in Step 1, a multiresolution approach may be applied or a new simulation model created. However, these options require a significantly higher level of effort. The combination of simulation model and travel demand model should cover the temporal and geographic scope defined in Step 1. For example, if a reliability analysis is desired for the p.m. peak period and the current travel demand model is a daily model and the simulation model is a peak hour model, a peak period model will need to be specifically developed, run, and tested before beginning the analysis.

Step 3: Simulation Modeling Method Selection

The simple and multiscenario methods report reliability using outputs from a simulation model. Both methods are explained in section 3.4. The simple method uses a generalized equation to calculate reliability and is therefore not specific to local conditions or behaviors. The simple method is also limited in the type of alternatives it can be used to analyze. If the analysis needs to be specific to local conditions and behaviors, the multiscenario method should be used. The flow chart in Figure 5.4 details the process up to this point. One additional method in the flow chart is not discussed in this section: the *hybrid method*. The choice to use it, as opposed to the simulation multiscenario method, depends on whether the global IDAS tables are sufficient or the analysis needs to be tailored to local conditions and behaviors. The hybrid method is required if the global tables are sufficient and one of the alternatives to be analyzed requires a weather or construction scenario.

Step 4: Identify Alternative Conditions to Analyze

Once the model data and simulation method are confirmed, the analysts should proceed with identifying the alternatives and scenarios to be generated and analyzed.

a. In the case of the simple method, only the baseline condition needs to be run.
b. Hybrid method requires multiple scenarios, each representing a change in one, or a multiple, of the causes of congestion: demand, weather, and construction. These scenarios need only be run for the baseline (no-build) condition.
c. Multiscenario simulation method requires multiple scenarios, each representing a change in one, or a multiple, of the causes of congestion: demand, incidents, weather, and construction. Each scenario has to be run for each analysis strategy/alternative.

Step 5: Study Causes and Probabilities of Congestion

To determine which scenarios are required for the hybrid and multiscenario analysis, a study of the causes of congestion and their probability of occurrence needs to be completed. This type of study is very easy to complete if a monitoring and management tool is available for the study area; see section 3.5 for more information about monitoring and management tools. The purpose of the *probability of occurrence* study is to develop a table similar to Table 5.9, which was created as part of the ICM project, that details the percent of time each scenario exists in a typical year/month/week (depending on seasonal variations). The following definitions were established for the *probability of occurrence* study:

a. Travel Demand: High travel demand is defined as greater than 7,500 vehicles per hour (vph); medium demand is between 6,900 and 7,500 vph; and low demand is less than 6,900 vph.

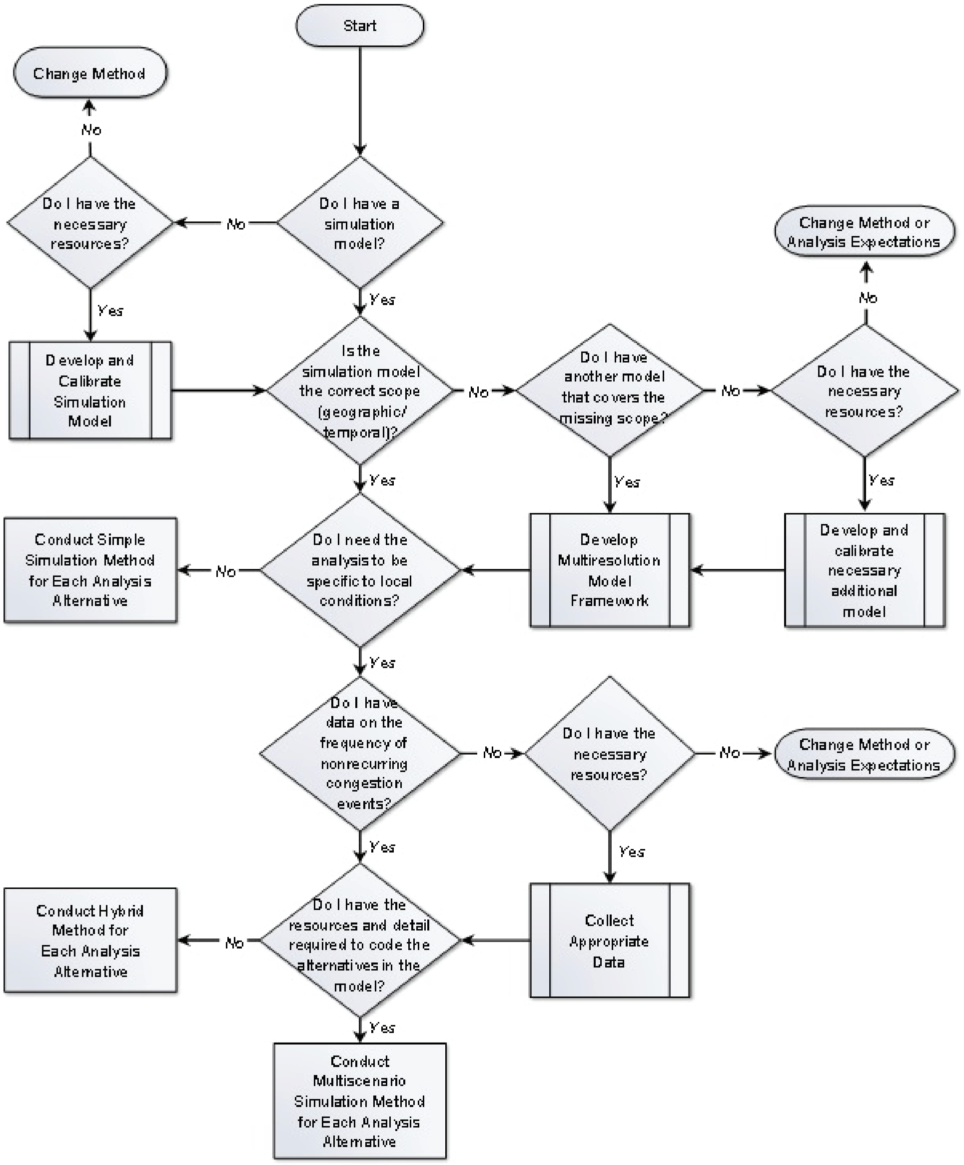

Figure 5.4. *Simulation method flow chart.*

b. Incidents: A major incident is defined as two or more general-purpose lanes affected, while a minor incident is defined as one general-purpose lane (or one general-purpose lane and shoulder) affected.

c. Inclement Weather: Inclement weather is defined as raining more than 0.1 inch per hour or having conditions of ice or snow.

Step 6: Develop Scenarios for Evaluation

Once the distribution of the various causes of congestion is analyzed, the results are used to develop scenarios for evaluation (combinations of influencing factors); each line in Table 5.9 is an example of a scenario. The monitoring and management tool

TABLE 5.9. DISTRIBUTION OF OPERATING CONDITIONS FOR US-75 DALLAS

Demand	Incident	Inclement Weather	Number of Hours	Percent
Med	No	No	247	33.9%
Low	No	No	136	18.7%
High	No	No	134	18.4%
Med	Minor	No	79	10.8%
High	Minor	No	55	7.5%
Low	Minor	No	55	7.5%
Low	No	Yes	9	1.2%
Med	No	Yes	5	0.7%
Med	Major	No	4	0.5%
Low	Major	No	2	0.3%
Low	Minor	Yes	2	0.3%
High	Major	No	1	0.1%
Med	Minor	Yes	0	0.0%
High	No	Yes	0	0.0%
High	Minor	Yes	0	0.0%
High	Major	Yes	0	0.0%
Med	Major	Yes	0	0.0%
Low	Major	Yes	0	0.0%

or data collection plan should be organized in such a way that the number of days (or hours of delay) related to each scenario can be determined.

Step 7: Run the Model and Output Results

The various alternatives will then need to be run and the performance measures calculated.

a. Simple method: the baseline model needs to be run. The travel times are then extracted from the model results and used in the sketch-planning equations found in Step 4 in Section 5.1.

b. Hybrid method: a baseline model run is needed for each scenario. Additional guidance on creating the scenarios is provided in Section 5.5. The travel times from each modeled scenario are extracted and used in the same sketch-planning equations used for the simple method. The results from the multiple sketch-planning analyses are then weighted using the probability of occurrence and combined for each analysis strategy/alternative.

c. Multiscenario method: a model needs to be run for each alternative strategy/alternative for each scenario (i.e., four strategies including the baseline and eight scenarios results in 32 model runs). Section 5.5 provides additional guidance on the development of these model scenarios. The process of generating reliability metrics from the simulation models is complicated. Nevertheless, essentially the variability in travel times extracted from the various scenarios for each strategy/alternative, weighted by their probability of occurrence, *is* the reliability for that strategy/alternative. Appendix D provides additional information on completing a multiscenario post-processing method based on probability of occurrence. Appendix F provides guidance from FHWA describing the generation of various travel time reliability performance measures from simulation models, including those analyses employing multiscenario approaches.

d. The travel times for each of the methods can be extracted in different levels of geographic and temporal aggregation, varying from link-based to O-D pair-based and from 5 min to the entire model duration.

5.4 APPLYING MONITORING AND MANAGEMENT TOOLS AND METHODS

The SHRP 2 Project L02 provides detailed guidance on Establishing Monitoring Programs for Travel Time Reliability. The project's main product is a guidebook which describes how an agency should develop and use a Travel Time Reliability Monitoring System (TTRMS). The guidebook follows the block diagram presented in Figure 5.5 for purposes of describing the TTRMS.

The L02 guide covers the following aspects of the monitoring system:

- *Data Collection and Management*: the types and application of various types of sensors, the management of data from those sensors, and the integration of data from other systems that provide input on sources of unreliability (e.g., weather, incidents).

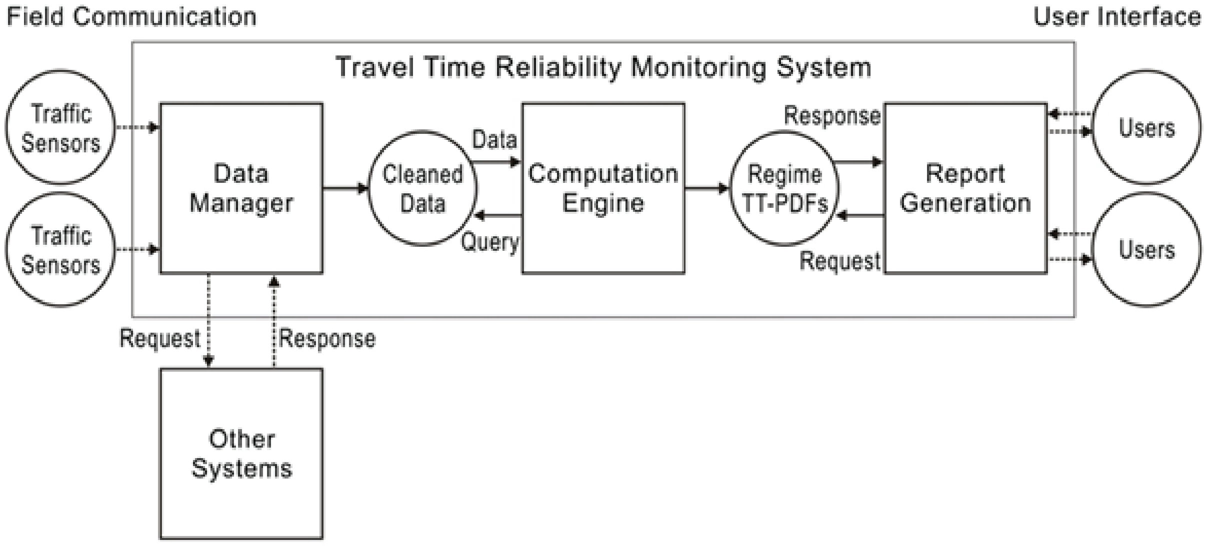

Figure 5.5. *Travel Time Reliability Monitoring System diagram.*
Source: SHRP 2 L02: Establishing Monitoring Programs for Travel Time Reliability, November 2010.

- *Computational Methods*: how probability density functions can be derived from the variety of data sources. This includes the process of generating travel time probability density functions that can be used to derive a variety of reports to users.
- *Applications*: a discussion about five real-world case studies that were conducted as part of the project as well as a set of use cases that show how the methods can be applied.
- *Analytical Process*: a beginning-to-end discussion about how travel time reliability should be analyzed under various conditions.

Regarding data collection and management, the L02 guide discusses the various technologies available for collecting travel times, the foundation of a TTRMS and the distinctions between roadway-based and vehicle-based equipment. Collecting travel time data continuously is preferred so that *travel time density functions* can be developed. These are either probability density functions or cumulative density functions and are used to describe the reliability characteristics of a corridor or a trip. Augmenting travel times are data on nonrecurring disruptions: incidents, weather, work zones, and special events. (A discussion of demand, i.e., volume, is not included but should be considered in developing a TTRMS.)

Regarding computational methods, the L02 guide presents data processing methods in terms of the following:

- *Network Concepts*: how the TTRMS represents travel times. These include the idea that monuments (i.e., points on the network where measurements are taken) should be placed in the middle of physical links away from interchanges and intersections.
- *Trip-Making Concepts*: how the TTRMS represents trip travel times.
- *Operating Conditions and Regimes*: how the impacts of influencing factors are studied. Regimes are combinations of the causal factors (in terms of the percent of occurrence) that result in different levels of congestion and unreliability.
- *Imputation*: how the TTRMS should impute estimates for missing or invalid data. Several algorithms are presented for imputing missing data.
- *Segment Travel Time Calculations*: the steps and computations that transform raw sensor data into observations of segment travel times. Methods are presented to convert measurements—both from individual roadway sensors and from vehicle-based systems—into travel times across a segment (i.e., multiple links).
- *Route Travel Time Computations*: how travel times are assembled into probability density functions for segments and routes. A method is presented to combine the travel time distributions from short segments into a single travel time distribution for an entire route that is statistically defensible, given the correlation that exists between travel times on adjacent segments.

- *Causal Factor Analysis*: how the TTRMS can be used to examine the influence on reliability of various causal factors, both internal and external. The basis of the diagnostics presented in this section is the development of separate travel time distributions for a facility based on the presence of an "influencing factor." Thus, separate travel time distributions are developed when incidents, inclement weather conditions, work zones, and special events are present. Comparing the size and shape of these distributions presents the analyst with an understanding of what is causing congestion and unreliable travel. Figure 5.6 illustrates an example.

NCHRP Project 3-68: Guide to Effective Freeway Performance Measurement is another great resource for data collection and processing methods (*8*).

A reliability analysis using the monitoring and management tools and methods would be expected to follow the steps described in this section. Many agency ITS or operations programs have already conducted many if not all of these steps.

Step 1: Develop Data Collection System and Data Archive

The data collection activity for reliability will focus on the collection of travel time. The methods of collecting travel time data are detailed in Appendix E of this document. The probe data systems will directly report travel time to the archive while the spot data systems will report point speeds along a road segment. By knowing the distance between detectors and the locations of detectors, the travel time is estimated. The

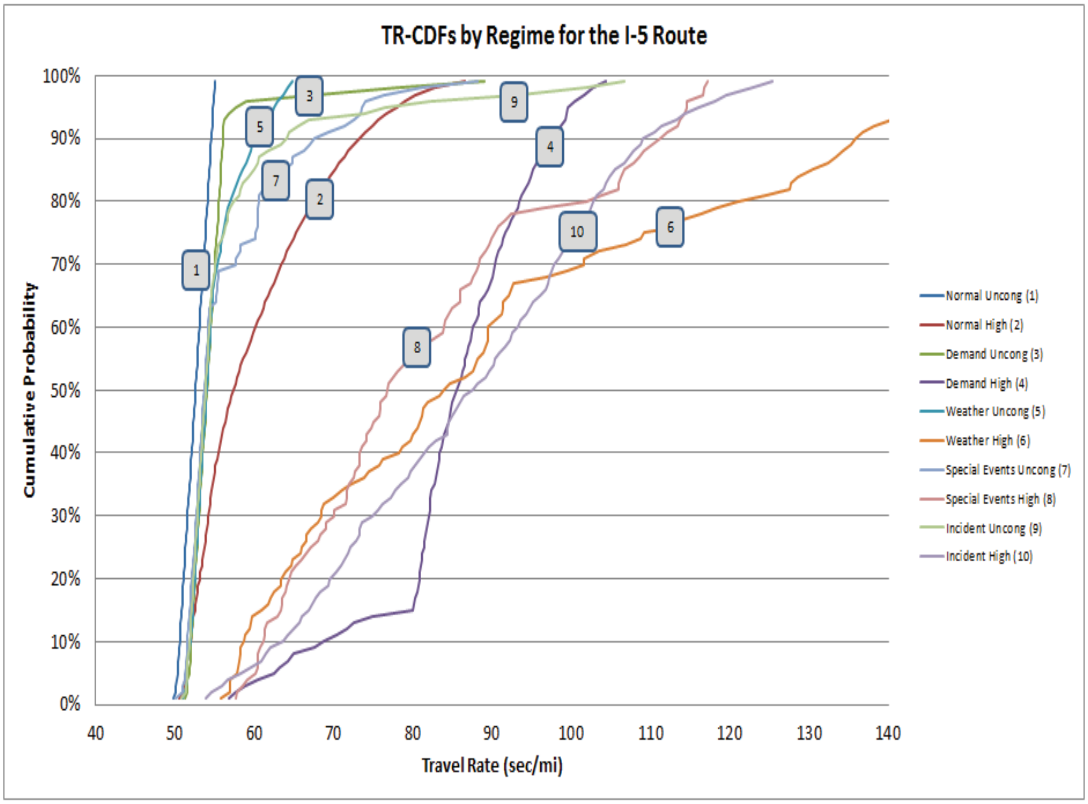

Figure 5.6. *Causal factor analysis example (7).*

Florida DOT uses both real-time roadside detection and probe data sources for their data collection efforts (see the Florida DOT case study for additional information). Los Angeles Metropolitan Transit Authority (MTA) is considering a similar approach (see the LAMTA case study), while North Central Texas Council of Governments (NCTCOG) is considering moving forward with its monitoring and management system using probe data from an outside vendor (see the NCTCOG case study).

The data archive must be developed to receive the travel time or speed plus any other data (e.g., incident data, road characteristics, and so forth). The archive requirements have previously been described in detail. The major process requirements for an archive are data storage, data transformation, data quality check and repair, calculation, and reporting. The archive also should permit a range queries by various users.

Step 2: Collect and Transmit Data to the Data Archive

The data collection will be conducted automatically by the deployed field devices. These data, collected continuously, and a communications network that connects all the field devices with the central computer that operates the data archive must be deployed in order for the system to function. The communications network must have enough bandwidth to transmit data from all field devices to the archive on a very frequent basis, typically once every 30 seconds. It is important that the field devices and the communications network be maintained properly or the system will not provide quality, timely data.

Step 3: Store the Data

The collected data must be stored by the central data archive. As the collected data are continuously transmitted from each field device, the amount of storage needed is large. Typical operations of an archive will maintain the raw field collected data in a buffer for several days and then erase them. The raw data are written to storage and transmitted to the archive processor for transformation and quality checks. The transformed, checked, and repaired data are also sent to storage. Depending on the amount of available storage, the raw data may be kept for some time, possibly a year, and then erased or stored off-line. The repaired data are usually kept for several years in primary storage and then could continue to be kept or stored off-line.

Step 4: Transform and Check for Data Quality

The stored raw data must be transformed into a format usable for the data quality checks and calculation processes. The specific format needed for the data will depend on the field device collecting the data, the specific data quality checks being conducted, and the measures being calculated from the data. Data quality checks have been discussed in detail in previous sections. As mentioned, it is also important to report the data quality through metadata. This provides the user of the data a sense of the quality of the data being used.

Step 5: Calculate Reliability

The archive must be developed to conduct the necessary calculations to determine the reliability of road segments. The actual formulas used to calculate reliability indices are detailed in the references provided in this document. Since travel time is the basis for all travel time reliability indices, once the travel time data are made available then the calculations themselves are simple for the computer to process. The most common reliability factors are the buffer time index, the travel time index, and the planning time index.

Step 6: Report Reliability

Reporting reliability is the most complicated part of the reliability process. Reliability can be described in many possible ways in visual terms. Some of those ways were described in the previous sections. The archive must allow customized queries by different users as well as preset reports showing specific road segments and times. Visual graphics are often used to show reliability and the impacts on congestion. Agencies across the United States provide examples of reliability visualization.

Case Study: Denver Region Implements Inexpensive Pilot System to Monitor Reliability

The Denver Regional Council of Governments (DRCOG), in partnership with the City of Englewood and Colorado Department of Transportation (DOT), recognized the need to start collecting mobility and travel time data on their arterial network to support their long-range planning process. In a pilot effort, they implemented an inexpensive arterial performance monitoring system along a 7-mi stretch of Hampden Avenue, a major arterial in Denver. The system consists of Bluetooth travel time detectors, queue length detectors, and volume counters installed at various locations throughout the corridor to monitor travel time and planning time indices. The system will be operational in spring 2013. Continuous monitoring of corridor performance will provide Colorado DOT and decision makers with quantifiable information on the reliability impacts of specific operations improvements that are implemented along the corridor, as well as the sum impact of all improvements made to the corridor or network. Potential operations improvements include traffic management (e.g., signal retiming, ITS deployment, intersection improvements, geometric improvements, and roundabouts), incident management, pavement maintenance, bridge maintenance, transit, nonmotorized facilities, freight and goods movement, winter operations, and capacity expansion projects.

The monitoring results will be used to develop a portfolio of operations strategies that were evaluated, selected, designed, and implemented within a performance-based system. The system will demonstrate to decision makers, taxpayers, and users that projects were selected to meet specific performance goals, were implemented as high priority projects based on performance criteria, and will provide specific user benefits in terms of improving corridor and system reliability. Incremental improvement in benefits over time will allow the partner agencies to shift resources to operations investments.

The case study demonstrates how DRCOG was able to use limited resources to implement an inexpensive reliability monitoring system to support corridor-based, data-driven planning efforts. Other agencies are sometimes allocated funds to collect data as part of a planned update of their region's travel demand model; it may be possible to use these funds to collect and process travel time data to support similar reliability monitoring efforts.

5.5 DEVELOPING MULTISCENARIO ALTERNATIVES

Multiscenario methods are most often associated with simulation model methods but can also be used in conjunction with model post-processing methods and even sketch-planning methods. The basis of a multiscenario method is the development of scenarios that together combine to represent the variable events that occur to create nonrecurring congestion. These events include incidents, weather, construction, special events (demand), and so forth.

Because of the increasing focus on the congestion caused by nonrecurring events, and the ability of transportation system management and operations (TSM&O) strategies to effectively improve travel conditions during nonrecurring events, much improvement has recently been made in enhancing the analysis of nonrecurring conditions. Two national initiatives have made significant advances in overcoming some of the analysis challenges related to identifying and quantifying nonrecurring congestion. These initiatives include the FHWA Integrated Corridor Management (ICM) initiative, which includes the development of an *Analysis, Modeling and Simulation (AMS) Guide* to aid practitioners at applying the developed analysis methods, and the ongoing FHWA development of a *Guide for Highway Capacity and Operations Analysis of Active Transportation and Demand Management Strategies*.

These projects are both developing analysis methods related to multiscenario methods. Although much more complex in their actual application, these analyses follow several general steps, including

1. Identification of the causes of nonrecurring congestion in a region;
2. Identification of the negative impacts of these nonrecurring conditions (e.g., reduced capacity caused by rain conditions);
3. Modification of analysis models and routines to be able to model baseline nonrecurring scenarios;
4. Identification of the impact of TSM&O and traditional projects on these nonrecurring conditions;
5. Identification and incorporation into the analysis of appropriate measures of effectiveness that are capable of quantifying the benefits;
6. Adjustment and development of modeling tools and methods to support the analysis; and
7. Effective presentation and explanation of results.

The basic premise behind the multiscenario method is to separately analyze recurring and various nonrecurring conditions as different scenarios and then sum the results of all the scenarios, weighted to the frequency with which each individual scenario is anticipated to occur in a typical year. To accomplish this, the analyst will need to compile data on historic patterns for demand variability, weather patterns, incident occurrence, and work zones.

To develop scenarios representing these nonrecurring conditions, the analyst will need to make modifications to the baseline parameters in the model used to reflect the capacity loss of these nonrecurring conditions. As part of the development of the *Guide for Highway Capacity and Operations Analysis of Active Transportation and Demand Management Strategies*, a number of baseline capacity constraints have been mapped to various nonrecurring conditions based on data in the 2010 Highway Capacity Manual (HCM). Table 5.10 presents the capacity reduction factors related to various inclement weather conditions. Table 5.11 presents capacity reduction factors related to various incident types. Table 5.12 presents capacity reduction factors related to various work zones.

TABLE 5.10. CAPACITY REDUCTION BASED ON NONRECURRING WEATHER TYPES (*9*)

Weather Type	Capacity Range (Percent)
Rain	2–14
Snow	4–22
Low temp	1–9
High wind	1–2
Visibility	1–12

TABLE 5.11. CAPACITY REDUCTION BASED ON NONRECURRING INCIDENTS (PERCENT) (*10*)

Number of Lanes (1 Dir)	Shoulder Disablement	Shoulder Accident	One Lane Blocked	Two Lanes Blocked	Three Lanes Blocked
2	5	19	65	100	N/A
3	1	17	51	83	100
4	1	15	42	75	87
5	1	13	35	60	80
6	1	11	29	50	74
7	1	9	25	43	64
8	1	7	22	37	59

TABLE 5.12. CAPACITY REDUCTION RELATED TO WORK ZONES (PERCENT) (*11*)

Original Lanes	Work Lanes			
	1	2	3	4
1	?	N/A	N/A	N/A
2	67	?	N/A	N/A
3	77	54	?	N/A
4	84	65	46	?

The capacity reduction factors presented in the tables may be used to create various baseline scenarios that represent one or a combination of these various nonrecurring conditions. The development and analysis of additional scenarios representing different nonrecurring conditions need to be carefully considered, however, as each additional scenario will require additional time and resources to create and run. In addition, it is important for the analyst to remember that in order to conduct a benefit–cost analysis of TSM&O strategies, each of the scenarios will need to be run twice, once as baseline without the strategy and once as an alternative scenario with the strategy deployed. Therefore, adding additional nonrecurring conditions scenarios can quickly multiply the number of model runs that are required.

It is recommended that the analyst review the data compiled on the frequency of nonrecurring events in order to develop a reasonable number of scenarios that may be modeled. Table 5.13 presents a sample comparison of the frequency of occurrence of various incident and bad weather conditions compared with varying levels of travel demand (presented as percentiles of the volume distribution) prepared for a sample section of the I-580 corridor in California as part of the development of the FHWA *Guide for Highway Capacity and Operations Analysis of Active Transportation and Demand Management Strategies*.

TABLE 5.13. SAMPLE SCENARIO PROBABILITIES: I-580 CORRIDOR (*12*)

Scenario	Capacity Reduction	5% Demand	20% Demand	50% Demand	80% Demand	95% Demand	Row Totals
No Incidents, Good Weather	0%	6.04%	15.10%	18.12%	15.10%	6.04%	60.40%
Single Lane Closure, Good Weather	42%	2.16%	5.40%	6.48%	5.40%	2.16%	21.60%
Dual+ Lane Closure, Good Weather	75%	0.07%	0.19%	0.22%	0.19%	0.07%	0.74%
No Incidents, Bad Weather	7%	1.26%	3.15%	3.78%	3.15%	1.26%	12.60%
Single Lane Closure, Bad Weather	49%	0.45%	1.13%	1.35%	1.13%	0.45%	4.50%
Dual+ Lane Closure, Bad Weather	82%	0.02%	0.04%	0.05%	0.04%	0.02%	0.16%
Column Totals	—	10.00%	25.00%	30.00%	25.00%	10.00%	100.00%

The probabilities of various scenarios would be expected to vary depending on the region and even the individual corridor; therefore, it is recommended that analysts assemble and analyze the probabilities of nonrecurring conditions individually for each study. Once these data have been analyzed, the analyst can prioritize various scenarios to be developed and analyzed based on their probabilities. For example, if resources are not available to run all scenarios, the analyst may want to discard those strategies with very low probabilities.

Once all the scenarios have been analyzed for both the baseline and the alternative scenario, the incremental change in benefits for each scenario would be weighted according to its probability and summed to provide an estimate of benefits across all recurring and nonrecurring conditions.

5.6 REFERENCES

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6

BENEFIT–COST ANALYSIS

Incremental benefit–cost analyses are used when alternatives are mutually exclusive and where an economical solution must be identified. An incremental benefit–cost analysis can reveal whether the incremental cost of a higher-cost project is justified by the incremental benefits gained (given all other factors being equal). Additionally, an incremental benefit–cost analysis will help identify whether a lower-cost alternative that realizes proportionally more benefits is a more optimal solution.

An incremental benefit–cost analysis is defined as the incremental benefits divided by the incremental cost.

$$\text{Incremental benefit–cost} = \frac{\text{incremental benefits}}{\text{incremental costs}} \tag{6.1}$$

To calculate the incremental benefit–cost, the following steps should be followed:

1. Rank the options in order of increasing cost.
2. Beginning with the lower-cost option of two or more alternatives, move to the next-higher-cost option and calculate the incremental benefit–cost ratio.
3. If the incremental benefit–cost ratio is equal to or greater than the target incremental benefit–cost ratio, discard the lower-cost option and use the higher-cost option as the comparison basis with the next-higher-cost option.
4. If the incremental benefit–cost ratio is less than the target incremental benefit–cost ratio, discard the higher-cost option and use the lower-cost option as the basis for comparison with the next-higher-cost option.
5. Repeat the steps until all options have been analyzed.

Color versions of the figures in this chapter are available online:
http://www.trb.org/Main/Blurbs/168856.aspx

The costs need to be developed for each analysis alternative; these costs are the same in any benefit–cost analysis. FHWA's *Intelligent Transportation Systems Benefits and Costs* report is a good guide to the costs of some of the congestion reduction strategies. The remainder of this chapter details the calculation to monetize the benefits of improved reliability.

To perform an incremental benefit–cost analysis incorporating reliability, the values must be quantified. The valuation approach of reliability is based on the recent work of Small, Winston, and Yan (*1*). They adopted the quantitative measure of variability as the upper tail of the distribution of travel times; specifically, the difference between the 80th and 50th percentile travel times. The authors argue that this measure is better than a symmetric standard deviation, because in most situations being late is more crucial than being early. Many regular travelers will tend to build a safety margin into their departure times that will leave them an acceptably small chance of arriving late (e.g., planning for the 80th percentile travel time would mean arriving late for only 20% of the trips).

This process monetizes the additional time that travelers build into their trips to ensure they arrive at their destination on time at least 80% of the time. An argument has been made that the value a traveler subconsciously associates with this extra time (value of reliability, VoR) is different from the value they associate with the actual travel time (value of time, VoT). Therefore this process uses "travel time equivalents," which is the combination of the typical (average) travel time index and reliability travel time index. That is, reliability is equilibrated to average travel time.

1. Compute the 80th and 50th percentile TTI's using the SHRP 2 L03 data-poor equations:

$$TTI_{80} = 1 + 2.1406 * \ln(TTI_{mean}) \tag{6.2}$$

$$TTI_{50} = TTI_{mean}^{\ 0.8601} \tag{6.3}$$

   where

   TTI_{80} is the 80^{th} percentile TTI and
   TTI_{50} is the 50^{th} percentile TTI

2. The calculation of travel time equivalents is then

$$TTI_e = TTI_{50} + a * (TTI_{80} - TTI_{50}) \tag{6.4}$$

   where

   TTI_e is the TTI equivalent on the segment and
   a is the Reliability Ratio (VoR/VoT), set equal to 0.8 for now[1]

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[1] Further work is needed to more tightly define the Reliability Ratio. SHRP 2 Project C04 suggests a range of 0.5 to 1.5, but a review of past studies suggests that the range is more in the 0.9 to 1.2 range. Previous research also indicates that the value of reliability varies by trip purpose. Users should strive to develop their own values for the reliability ratio based on the latest research and local conditions. Additional information on the monetary value of reliability is provided in Chapter 5 of the SHRP 2 L05 guide.

The first term in Equation 6.4 accounts for the value of typical travel time, as measured by the median value. The median is selected for use here because if the overall mean TTI were used, it would include some of the variability from the travel time distribution, leading to double counting when the reliability term is added. Separate travel time equivalents can be computed for personal and commercial travel by using different values for the reliability ratio.

3. Compute total equivalent delay based on the TTI_e:

$$\text{Total Equivalent Delay} = \left(\frac{TTI_e}{\textit{Free Flow Speed}} - \frac{1}{\textit{Free Flow Speed}} \right) * \text{VMT} \quad (6.5)$$

where

TotalEquivalentDelay is in vehicle-hours,
(TTI_e/FreeFlowSpeed) is the unit travel rate (hours/mile), and
VMT is the vehicle-miles traveled (mile).

Delay may be decomposed into passenger and commercial portions using different travel time equivalents and VMT values.

Total equivalent delay is the output of this methodology; it includes both recurrent delay and the additional nonrecurrent delay drivers need to anticipate arriving at their destinations on time 80% of the time. To monetize this delay, it needs to be multiplied by the regular value of time used in any benefit–cost analysis.

This method was evaluated in multiple case studies. The Knoxville TPO case study used this method to quantify the value of travel time (including the reliability component) for selected projects in their recently completed Regional ITS Architecture. The Colorado DOT case study calculated the benefits of arterial operations improvements as part of a traffic operations pilot project, while the SEMCOG case study applied the method to its existing program trade-off methodology to identify opportunities for incorporating reliability strategies. This is seen as a first step toward including reliability in local project evaluations and educating stakeholders on the importance of travel time reliability.

6.1 APPLICATION TO SKETCH-PLANNING METHODS

The methodology just outlined is directly applicable to the sketch-planning method. Both the sketch-planning and benefit–cost methodology were developed under SHRP 2 L03; therefore, the outputs from sketch planning can be seamlessly input into the benefit–cost analysis. Additional to the outputs from the sketch-planning process, vehicle-miles traveled (VMT) is required to perform the benefit–cost analysis. VMT can be calculated using link volume and length.

6.2 APPLICATION TO MODEL POST-PROCESSING METHODS

If IDAS is being used as the model post-processor, the benefit–cost calculation is completed within the tool itself. However, not all strategies are included in IDAS, and only incident-related delay is assessed within the tool. For the strategies not included in IDAS an outside calculation will need to be conducted, which can be completed using the incident delay from IDAS in the SHRP 2 L03 benefit–cost calculations.

If a multiscenario approach was followed, the reduction in nonrecurring delay is determined with the demand model and the benefit–cost results from IDAS can be used. The results should be combined using the weights determined in the probability of occurrence for each scenario. Appendix D provides additional information on completing a multimethod post-processing method based on probability of occurrence, and Appendix F provides guidance from FHWA describing the generation of various travel time reliability performance measures using model post-processing methods.

6.3 APPLICATION TO SIMULATION METHODS

In the case of the simple and hybrid methods, measures of reliability are not explicit outputs from the simulation model, but instead the results feed the sketch-planning and post-processing methods; therefore, the benefit–cost calculation will follow the process discussed in those sections.

When using a multiscenario approach, each scenario represents a certain percentage of the year's operational conditions, as determined by the weighting factor; as such, the 50th and 80th percentiles can be determined directly from the results and used in Equation 6.4 in the SHRP 2 L03 method.

6.4 APPLICATION TO MONITORING AND MANAGEMENT TOOLS AND METHODS

Because monitoring and management tools are designed to assess what exists in the field and not to analyze strategies, they are not typically associated with benefit–cost analyses. They can, however, be used to look back at the investments that were made to address congestion and to compare those investments to the improvements in the operations of the system. In this regard, the SHRP 2 L03 method can be used to assess the actual benefits achieved.

6.5 CASE STUDY: KNOXVILLE APPLIES BENEFIT–COST ANALYSIS TO SKETCH-PLANNING RESULTS

Using the results of their sketch-planning analysis of the reliability impacts of Regional ITS Architecture projects, the Knoxville TPO staff conducted a benefits analysis to determine the annual delay savings associated with each project. First, they used to TTI_{mean} to calculate the 80th and 50th percentile TTIs using Equations 6.2 and 6.3 from this technical reference. For example, for the baseline condition for Segment 1 of the Smartway Expansion Project, TTI_{80} and TTI_{50} were calculated as follows:

$$TTI_{80} = 1 + 2.1406 * \ln(TTI_{mean}) = 1 + 2.1406 * \ln(1.109) = 1.2223$$

$$TTI_{50} = TTI_{mean}^{\;0.8601} = (1.109)^{0.8601} = 1.0934$$

Next, they computed travel time equivalents (TTI_e) using Equation 6.4 in order to equilibrate reliability to average travel time for each project, and then they calculated total equivalent delay using Equation 6.5. For example, for the baseline condition for Segment 1 of the Smartway Expansion Project, TTI_e and total equivalent delay were calculated as follows:

$$TTI_e = TTI_{50} + a * (TTI_{80} - TTI_{50}) = 1.0934 + 0.8 * (1.2223 - 1.0934) = 1.1965$$

$$\text{Total Equivalent Delay} = \left(\frac{\text{TTIe}}{\text{FFS}} - \frac{1}{\text{FFS}}\right) * \text{VMT} =$$

$$\left(\frac{1.1965}{65} - \frac{1}{65}\right) * \left(\frac{200585}{2}\right) = 303.3 \text{ hours}$$

The annual delay savings was calculated based on the difference in total equivalent delay between the baseline and improved scenarios, multiplied by the number of effective days per year. An excerpt of results for the benefits analysis is provided in Table 6.1.

TABLE 6.1. KNOXVILLE TPO SKETCH MODEL ANNUAL DELAY BENEFITS EXCERPT

Segment Name	VMT (Miles)	Baseline Equivalent Delay (hours)	Improved Equivalent Delay (hours)	Equivalent Delay Benefit (hours)	Annual Delay Benefit (hours)
Segment 1	200,585	303	169	134	34,920
Segment 2	228,505	3,621	2,642	979	254,505
Segment 3	845,083	13,334	9,699	3,635	944,973

They determined that the Smartway Expansion on I-40 and I-75 west of Knoxville, the Smartway expansion on US-129 /SR-115 (Alcoa Highway), and the HELP service patrol expansion projects yielded the highest benefits in terms of total equivalent delay. Although project costs were not available at the time of the case study, it is possible to monetize the results by applying the average value of time to the total delay savings and comparing it with project cost to estimate the cost-effectiveness of the project.

6.6 CASE STUDY: SOUTHEAST MICHIGAN COUNCIL OF GOVERNMENTS' USE OF REPRESENTATIVE CORRIDORS TO ESTIMATE REGIONWIDE DELAY

The Detroit MPO, the Southeast Michigan Council of Governments (SEMCOG), wanted to incorporate reliability into its existing process for assessing the effectiveness of investment strategies on regional transportation benefits. Previously, this analysis examined hours of recurring delay per VMT. SEMCOG incorporated reliability by estimating nonrecurring hours of congestion delay in addition to typical recurring hours of congestion delay. With limited resources and time to invest in the analysis, SEMCOG decided to apply sketch-planning methods to estimate total delay in the corridor. The staff reduced the geographic scope of the analysis by using representative freeway corridors with operational characteristics (e.g., average traffic volume, interchange density, directional flows, and surrounding land use) that are generally representative of other corridors throughout the Detroit region. The representative corridors included (1) an urban radial (Interstate 96); (2) a suburban radial (Interstate 75); and (3) a suburban beltway (Interstate 275).

SEMCOG developed a regionwide analysis by identifying the percent of regional VMT that each representative corridor accounts for. Based on professional judgment and historical traffic data, SEMCOG determined that urban radials carry 37% of regional VMT, suburban radials carry 30% of regional VMT, and suburban beltways carry 33% of regional VMT. Because they opted to use a rate-based measure of effectiveness (MOE), SEMCOG was able to use the delay rate from the representative corridors as a proxy for delay on all other similar corridors in the region.

The regional travel demand model was used to obtain input data on a link-by-link basis, including peak period volumes, capacities, number of lanes, VMT, and speeds (congested and posted). Link data were averaged across the representative corridors, while free-flow and congested travel times were estimated by dividing the link lengths by the compiled travel speeds. They estimated recurring delay by subtracting free-flow travel times from congested travel times using Equation 5.7. Incident delay was estimated using IDAS lookup tables based on number of lanes, length of the peak period, and volume to capacity ratio. The total equivalent delay was estimated using the data-poor algorithms in Equations 6.4 and 6.5. The baseline recurring, incident, and total equivalent delay by representative corridors and regionwide is summarized in Table 6.2.

TABLE 6.2. SEMCOG SKETCH MODEL BASELINE CONDITIONS

Representative Corridor	Percent of Regional VMT	Recurring Delay per 1,000 VMT (hours)	Incident Delay per 1,000 VMT (hours)	Total Equivalent Delay per 1,000 VMT (hours)
Urban Radial	37%	1.05	1.23	4.06
Suburban Radial	30%	4.04	1.00	8.48
Suburban Beltway	33%	2.56	2.46	8.36
Regional Total (VMT weighted average)		**2.45**	**1.57**	**6.80**

SEMCOG evaluated several reliability mitigation strategies along the corridors, including freeway management (surveillance, monitoring, ramp metering), incident management (freeway service patrols), and traffic signal coordination. SEMCOG assumed that the roadway operational investments would reduce the average incident duration by 20%, reduce the total number of incidents by 10%, and increase capacity by 5% compared with existing conditions. They used Equation 5.9 from this technical reference to estimate the impact of these strategies on nonrecurring congestion.

To estimate regional benefits, they extrapolated the benefits of the study corridor to representative corridors and then to the region as a whole. This allowed them to develop an improved performance curve to compare funding levels to reliability performance in conjunction with average travel time performance (Table 6.3).

TABLE 6.3. SEMCOG SKETCH MODEL IMPROVEMENT BY FUNDING LEVEL

Representative Corridor	Percent of Regional VMT	Savings in Total Delay per 1,000 VMT (hours)				
		$0M	$25M	$50M	$75M	$100M
Urban Radial	37%	4.06	3.06	2.56	2.05	2.05
Suburban Radial	30%	8.48	7.12	5.77	4.41	3.06
Suburban Beltway	33%	8.36	7.62	6.87	6.12	5.37
Regional Total (VMT weighted average)		**6.80**	**5.78**	**4.94**	**4.10**	**3.45**

The comparisons of the benefits estimated both with and without considering reliability show that investments in the operations strategies yield a much greater impact on total hours of delay, particularly at the lower investment levels. Small investments in these strategies result in a steep curve of reducing delay levels. Like the curve not considering reliability, the performance curve considering reliability (shown in Figure 6.1) illustrates a declining utility to higher investment levels and indicates that increased investment brings about lower incremental improvement for each dollar spent.

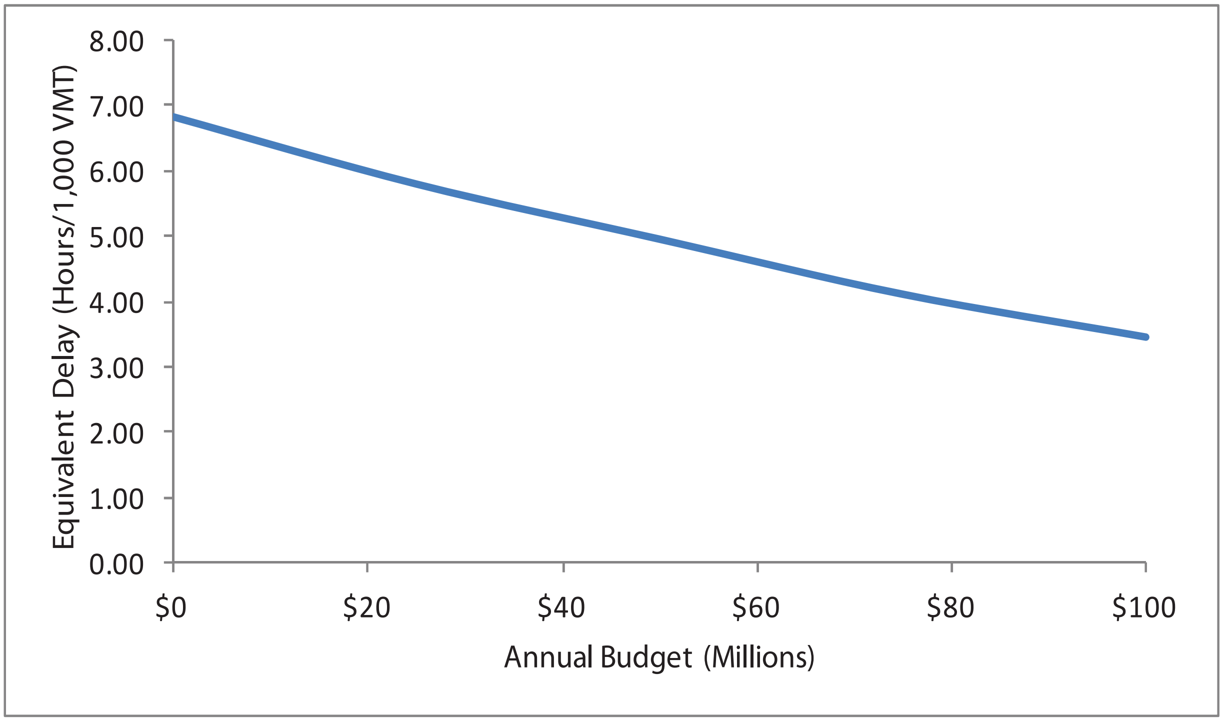

Figure 6.1. *SEMCOG equivalent delay by funding level.*

6.7 REFERENCE

1. Small, K.A., C. Winston, and J. Yan. 2005. Uncovering the Distribution of Motorists' Preferences for Travel Time and Reliability. *Econometrica* 73(4), 1367–1382.

7

IMPROVING PLANNING AND PROGRAMMING CAPABILITY

In most metropolitan areas, roadway congestion, delay, and unreliability continue to increase. At the same time, the potential of traditional strategies to increase capacity is constrained by both financial and physical impact considerations. As a result, transportation agencies today are under pressure to make more effective use of their existing roadway assets. Attention is turning toward how to provide the highest level of service from the current roadway system: by aggressively managing to minimize delay, maintaining speed and throughput, and improving reliability and safety. MAP-21, with its performance measurement emphasis, is adding to this impetus.

Transportation system management and operations (TSM&O), as a concept, is based on applying a broad range of strategies that respond to real-time events and constraints that reduce the level of service available from the existing roadway network. In particular, it focuses on minimizing the impacts of the various causes of nonrecurring congestion that account for more than one-half of total highway delay and most of the system unreliability, and that also impact safety and emissions.

Despite these positive features, TSM&O as a program has not been mainstreamed. Many states, local governments, and regional planning entities have no ongoing formal program to fully deploy these strategies or utilize them to their fullest effectiveness for traffic management. They are often carried out on an ad hoc basis at the initiative of middle managers at the regional level, with little planning and no formal budget, and without the support of institutional features such as a clear policy commitment, a long-range plan, a sustainable budget, defined performance measures and evaluations, a top-level staff, and organized collaboration.

Color versions of the figures in this chapter are available online:
http://www.trb.org/Main/Blurbs/168856.aspx

7.1 CHARACTERISTICS OF TSM&O

TSM&O strategies are heavily dependent on a combination of technologies embodied in defined regional systems architectures. These strategies require relating key functions and players regarding the flow of information (detection, surveillance, communication, information management and analysis, etc.) with field procedures and protocols designed to manage incidents, maintain traffic flow and speed, and provide user information of various kinds. Some TSM&O applications can be developed and implemented by a single jurisdiction, if it is large enough. However, they require preplanned, real-time cooperation with the public safety agencies and the private sector. Other important applications are by definition multijurisdictional and require close cooperation among different transportation agencies and a strong regional framework.

TSM&O strategies are low cost, highly effective, and have very limited (if any) external impacts. Major costs relate substantially to staffing and ongoing operational management rather than initial capital investment. They can be implemented in relatively short timeframes on a networkwide basis. Their success and the ability to improve their effectiveness are highly dependent on situational awareness and related ongoing performance measurement and analysis. These characteristics are embodied in transportation management centers, the hallmarks of TSM&O and the presumptive nerve center control room for optimizing the mobility benefits of the transportation network in real time. These characteristics, however, are also substantially at odds with the traditional capacity and maintenance preoccupation of transportations agencies and the civil engineering culture, business processes, organization, and staff capacities that exist within them.

7.2 SHRP 2 RESEARCH

SHRP 2 research has identified the key dimensions of agency capability needed to improve TSM&O and its effectiveness. Capability refers to the essential preconditions to improving TSM&O activities and programs. Research under SHRP 2 L06, Institutional Architectures to Advance Operational Strategies, identified the key dimensions of capability associated with the more effective TSM&O programs of states and metropolitan areas. These include clear policy and objectives, planning and programming appropriate to TSM&O, comprehensive and standardized systems and technology, outcome-focused performance measurement, aligned organizational structures and appropriate staff technical capabilities, and close collaboration among key agencies.

The research has concluded that the development of these capabilities specifically suitable to TSM&O requires significant changes in the legacy conventions of DOTs (and other transportation agencies) at the programmatic, process, and organizational levels. In SHRP 2 L06, a capability improvement approach was developed to assist transportation agencies in evaluating their current capabilities in these dimensions and identifying strategies for improvement.

Planning and programming is one of the key dimensions of capability. Formal planning for TSM&O exists only in a tiny minority of state DOTs and MPOs. TSM&O does not easily fit into the conventional formal transportation planning and programming processes (state or regional) that are oriented toward the allocation of federal and state funds for large-scale, high-cost, long-term, and often disruptive facility capacity improvements. Thus, planning and programming is a key area where new capabilities, concepts, and methods are needed to ensure that TSM&O improvements are considered in response to their unique characteristics and potential, as well as on a level playing field with traditional capacity improvement options.

The SHRP 2 L05 project, Incorporating Reliability Performance Measures into the Transportation Planning and Programming Processes, considers technical tools and methods by which reliability—primarily addressed through TSM&O strategies—can be incorporated into planning and programming capabilities. The substantive focus of the framework in this chapter builds on the L05 material. In addition, it is consistent with key findings from a series of studies produced by the FHWA Office of Operations, in particular *Advancing Metropolitan Planning for Operations* and related studies, with special attention on the cooperation and collaboration dimension of capability.

The capability framework for improving planning and programming discussed further in this chapter takes a broad view and includes process and institutional considerations as identified by the SHRP 2 L06 research and related workshops held at the state DOT statewide level and at the level of metropolitan collaboration. The capability improvement framework is designed to help transportation agencies evaluate their current practices and evolve toward one that can fully capitalize on the potential of TSM&O.

7.3 LIMITS OF THE CONVENTIONAL REGIONAL PLANNING PROCESS

The characteristics of effective TSM&O that must be addressed during its planning (as described here) are substantially at odds with the historical nature of transportation planning and programming, including the focus, requirements, and methods developed in the planning community. The traditional, well-defined, long-range continuing, cooperative, and comprehensive (3C) process as conventionally applied, either by individual agencies or at the metropolitan multijurisdictional scale, tends to focus on defining and evaluating major capital improvements to capacity at the individual facility level, with a strong emphasis on minimizing negative impacts. The steps and methods are built into federal aid requirements and have been honed over a 50-year period. Even if TSM&O were incorporated into the current planning and programming conventions, existing processes and methods are inappropriate.

TSM&O as a strategy is becoming increasingly noted as a policy focus in concept, but it is rarely incorporated into agencies' mainstream policies and programs. In most agencies, decisions regarding selection and funding of TSM&O strategies occur outside of the statewide or regional planning processes. Instead, they are usually a set of informal and ad hoc activities focused on the initial implementation of well-understood, easy-to-implement strategy options and sometimes on their improvement and upgrades. This activity tends to be driven by mid-level, self-taught staff champions with strong commitment and the entrepreneurial skills to overcome lack of a formal planning and programming process. Almost no formal training exists in the special skills related to TSM&O development, implementation, and management.

7.4 LEARNING FROM BEST PRACTICE EXAMPLES

Successful strategies to improve capability in the planning and programming dimension can be drawn from the results of the SHRP 2 L06 research and the 13 state and regional TSM&O capability improvement workshops based on its findings, the L05 case studies, and the FHWA *Advancing Metropolitan Planning for Operations* case studies. In addition, the practices of a few leading state DOTs and MPOs that have made important progress in incorporating TSM&O into the planning process provide valuable examples.

7.5 CAPABILITY IMPROVEMENT FRAMEWORK

The capability improvement framework developed for L06 and adapted here for planning and programming, specifically, is an adaptation of the capability maturity model (CMM) that is widely used in the information technology (IT) industry to identify levels of improvement in technical processes needed to meet project goals. It combines into a single framework many key features of quality management, organizational development, and business process reengineering concepts that have long been used as strategic management tools in transportation agencies. Similar to the capability improvement framework adapted generally to TSM&O by SHRP 2 L06, a capability improvement framework specific to planning and programming includes the following:

1. Identifying essential dimensions of capability in agency process and organizational capabilities required for continuing improvement in planning and programming for TSM&O;
2. Specifying the criteria defining meaningful levels of improvement in each capability dimension; and
3. Providing descriptions of the major actions to improve capabilities to the next level.

7.6 KEY DIMENSIONS OF CAPABILITY

An examination of best practice, as suggested in Chapter 5, indicated the critical dimensions of planning and programming for TSM&O—as a program—that must be incorporated into the capability improvement framework. Both business processes and institutional and organizational change have been shown to be essential and synergistic. Seven critical dimensions are closely associated with more effective planning and programs:

1. *Organizational structure and staffing for TSM&O*: Is planning and programming for TSM&O appropriately accommodated in the agency's organizational structure, and are the needed staff technical capabilities identified and available?
2. *Planning cooperation and collaboration for TSM&O*: Are the key agencies involved in plan development and resource allocation appropriately aligned and working together productively?
3. *TSM&O goals and objectives*: Do the implementing jurisdictions' formal goals and objectives directly address TSM&O and the problems it is intended to ameliorate?
4. *TSM&O performance measurement*: Are performance measures appropriate to plan and evaluate TSM&O applications in customer terms being employed?
5. *TSM&O needs and deficiency analysis and forecasting*: Are methods in use to systematically determine appropriate strategy applications, both short-term and long-term?
6. *TSM&O plan development*: Is a plan prepared and resources allocated based on systematic evaluation and consideration of trade-offs with other strategies?
7. *TSM&O implementation and feedback*: Are planners adjusting TSM&O strategy, real-time field execution systems, procedures, and protocols in response to measured performance—both outputs and outcomes?

The first three of these dimensions are associated with institutional and organizational change within an agency or group of collaborating agencies and require senior management involvement. The latter four are associated with business process activities where a spectrum of improved methodologies are important and can be implemented by activity managers or technical managers.

7.7 LEVELS OF CAPABILITY

Four incremental levels of capability are used to assess an agency's or a region's current state and improvement target for each dimension of planning and programming. By definition, they are doable steps, each building on the one before. The steps lead away from informal, ad hoc, champion-based processes toward custom-tailored processes that are routinized, standardized, documented, and performance-driven, and supported by appropriate institutional and organizational structures. Each level's criteria and the relationships among the levels are illustrated in a general sense in Figure 7.1.

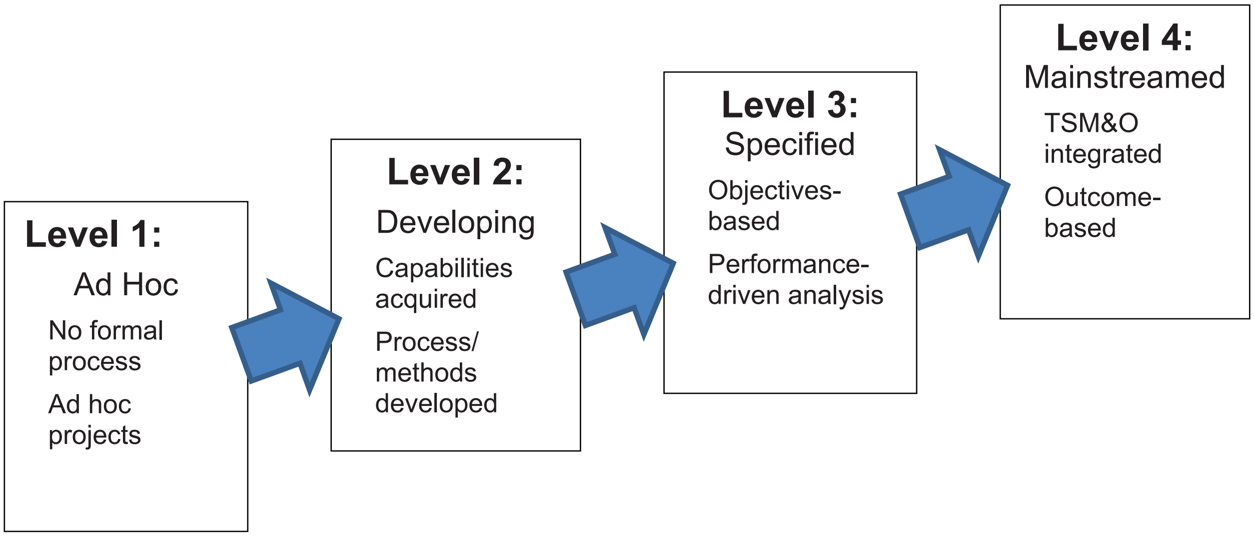

Figure 7.1. *General levels of capability for TSM&O planning.*

7.8 BASIC CAPABILITY IMPROVEMENT FRAMEWORK GUIDANCE TEMPLATE FOR TSM&O PLANNING

With the concept of dimensions and levels of capability as a framework, criteria were identified associated with each dimension and level combination and into the cells of a dimension/level matrix. The result is a guidance template for improving TSM&O planning and programming, as illustrated in Table 7.1. The criteria are based on logical increments in capability, with the agency goal of advancing from one level to the next through consistent and manageable steps, presumably achievable in a one-year time frame. Level advancement is accomplished through dimension-specific strategies discussed in section 7.10, “Dimension-Specific Strategies for Capability Improvement,” and detailed in Appendix G.

7.9 PRIORITIZING RULES OF CAPABILITY IMPROVEMENT

One of the key features of the capability improvement framework for TSM&O (and CMM in general) is its rules of application. They include the following considerations:

- The seven dimensions are interlinked vertically. The dimension at the lowest level of capability is usually the principal constraint to improvement in program effectiveness and therefore the highest priority to be addressed.
- Each of the dimensions included is essential and must be addressed, although some dimensions may be harder to deal with than others. Omitting improvement in any one dimension will inhibit continuous improvement of program effectiveness.
- Each incremental level of capability within a given dimension establishes the basis for the agency’s ability to progress to the next-higher level of effectiveness.

TABLE 7.1. CAPABILITY IMPROVEMENT FRAMEWORK GUIDANCE TEMPLATE FOR TSM&O PLANNING

Dimensions of Capability		**Levels of Capability**			
		Level 1: Ad Hoc	**Level 2: Developing**	**Level 3: Specified**	**Level 4: Mainstreamed**
INSTITUTIONAL	Organizational Structure and Staffing for TSM&O	*Planners with limited TSM&O background*	*Needed staff capabilities for planning identified and specified*	*Key relationships and needed capacities established*	*Formalized TSM&O organizational structure and position descriptions accommodated*
	Planning Cooperation/ Collaboration for TSM&O	*No formal planning or programming for TSM&O*	*TSM&O consideration at individual unit/agency level*	*Coordination/sharing of multiagency TSM&O planning via existing technical committees*	*TSM&O integrated into regional interagency multimodal planning (single process)*
	TSM&O Goals and Objectives	*None related specifically to dealing with improving TSM&O*	*TSM&O and related objectives understood/ incorporated as agency policy objective*	*Overall agency policy/objectives/ strategies adjusted to accommodate TSM&O*	*TSM&O given appropriate agency priority in plan/program*
PROCESS	TSM&O Performance Measurement	*None used for TSM&O planning and programming*	*Output data reported from monitoring and utilized in TSM&O strategy improvement*	*Objectives-based outcome measures developed/reported and utilized*	*Outcome measures incorporated into policy, strategy and project-level planning*
	TSM&O Needs/Deficiency Analysis and Forecasting	*No analysis of current or anticipated TSM&O shortfalls*	*Rules of thumb used to identify remediable TSM&O-related deficiencies*	*TSM&O-related forecasting used to identify future deficiencies and related strategies*	*Integration of TSM&O within overall forecasting and deficiency analysis*
	TSM&O Plan Development	*TSM&O improvements committed on opportunistic basis*	*Budget constrained evaluation of strategies on jurisdictional basis*	*Routine life-cycle comparison of TSM&O with capacity strategies*	*TSM&O integrated into overall agency priority-setting, planning and programming*
	TSM&O Implementation and Feedback	*Some TSM&O implemented*	*Performance reviewed on regular basis and applications adjusted*	*Performance outcomes used to "tune" and expand TSM&O strategies and improve procedures*	*Real time operational adjustments to optimize TSM&O synergies*

7.10 DIMENSION-SPECIFIC STRATEGIES FOR CAPABILITY IMPROVEMENT

Advancing from one level to the next within a given dimension of the capability improvement framework requires following defined strategies. The full matrix of seven dimensions and three possible level advancements (Level 1 to 2, Level 2 to 3, and Level 3 to 4) results in 21 sets of strategies, which are presented in full detail as Appendix G. Overall, the strategies provide generic guidance regarding the types of actions needed to improve an agency's capability in the seven critical dimensions of TSM&O planning and programming. The guidance suggestions are based on observed best practices in terms of what agencies have done to improve their capabilities in each dimension.

7.11 APPLYING THE GUIDANCE

The guidance is designed to be used in a self-evaluation process by the agencies involved in planning and programming for TSM&O. It is designed to apply to individual agencies (such as a state DOT) or a group of agencies that may wish to improve the existing regional transportation and planning processes to incorporate TSM&O. The self-evaluation process, using the capability improvement framework and guidance, consists of three steps:

Step 1: For each of the seven dimensions, list the agency's strengths and weaknesses based on its current state of play.
Step 2: Based on the criteria for each level in a dimension, identify the agency's current level, making reference to the level criteria in comparison to the strengths and weakness in Step 1.
Step 3: Starting with the dimension evaluated at the lowest level of capability, review the strategies in the guidance as an aid to define specific steps in a locally tailored strategy to meet the criteria of the next-highest level in that dimension. Repeat this process for each dimension. The strategies in the guidance are necessarily generic and therefore are intended to suggest key strategies only.
Step 4: Compile the locally tailored strategies for each dimension into an overall action plan, with priority accorded to the lowest rated dimension strategy.

A

ADDITIONAL RESOURCES

This technical guidance builds on several ongoing SHRP 2 and NCHRP research efforts that are providing analytical methods, case study examples, and new approaches related to transportation planning and performance measurement generally, and to reliability performance measurement in particular. Table A.1 provides annotated descriptions of references and other resources where users may obtain additional information to aid in their assessment of tools and methods, including descriptions of other parallel ongoing efforts. Table A.2 summarizes the relevant SHRP 2 projects and how they relate to this technical reference and the guide.

TABLE A.1 ADDITIONAL RESOURCES FOR ASSESSING RELIABILITY ANALYSIS TOOLS AND METHODS

ID	Subject	Title/Date	Description	Reference/URL
1.	Performance Measurement	HOV Performance Monitoring, Evaluation and Reporting Handbook, January 2006	Development of the HOV Performance Monitoring, Evaluation and Reporting Handbook was sponsored through the High-Occupancy Vehicle/Managed Use Lane Pooled Fund Study. The Handbook serves as a comprehensive guide to developing and conducting an HOV performance-monitoring program, including common objectives for HOV facilities, related performance measures and data requirements. Highlights of the handbook include data collection, reduction, and analysis techniques; potential funding sources; staffing and resource needs; and approaches for reporting HOV performance to various stakeholders.	https://hovpfs.ops.fhwa.dot.gov/hov_pfs_members/docs/projects/13/hovperfhandbook.pdf, accessed 12/8/2010
2.	Performance Measurement	NCHRP 03-68: Guide to Effective Freeway Performance Measurement: Final Report and Guidebook, August 2006	The guidebook provides detailed recommendations for developing and maintaining a comprehensive freeway performance-monitoring program. Step-by-step procedures describe the process for selecting freeway performance measures, data and modeling requirements, communicating performance results, and using measures in decision making.	http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_w97.pdf, accessed 12/7/2010
3.	Performance Measurement	NCHRP 07-15: Cost-Effective Performance Measures for Travel Time Delay, Variation, and Reliability, 2008	This guide presents methods to measure, predict, and report travel time, delay, and reliability. The framework considers various dimensions of surface transportation system performance, various data collection parameters and methods, analysis approaches, and applications that most effectively support transportation planning and decision making for capital and operational investments, as well as for quality-of-service monitoring and evaluation.	http://onlinepubs.trb.org/onlinepubs/nchrp/nchrp_rpt_618.pdf, accessed 12/13/2010
4.	Performance Measurement	NCHRP 8-70: Target-Setting Methods and Data Management to Support Performance-Based Resource Allocation by Transportation Agencies, 2010	This guide provides a performance measurement framework within which state DOTs and MPOs can develop and implement a performance-based resource allocation decision process. Guidance is provided on the process and methods for setting targets and establishing data systems to support performance-based resource allocation.	http://144.171.11.40/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2147, accessed 12/13/2010

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TABLE A.1 ADDITIONAL RESOURCES (continued)

ID	Subject	Title/Date	Description	Reference/URL
5.	Performance Measurement	Travel Time Reliability: Making It There On Time, All The Time, January 2006	Travel time reliability is significant to many transportation system users, whether they are vehicle drivers, transit riders, freight shippers, or even air travelers. Personal and business travelers value reliability because it allows them to make better use of their own time. Shippers and freight carriers require predictable travel times to remain competitive. Reliability is a valuable service that can be provided on privately financed or privately operated highways. Because reliability is so important for transportation system users, transportation planners and decision makers should consider travel time reliability a key performance measure. This report provides guidance on performance measures used to quantify travel time reliability, steps for developing reliability measures, and case studies in calculating reliability.	http://ops.fhwa.dot.gov/publications/tt_reliability/index.htm, accessed 12/7/2010
6.	Performance Measurement	Establishing Monitoring Programs for Mobility and Travel Time Reliability, SHRP 2 L02, active (estimated January 2012)	The objective of this project is to develop system designs for programs to monitor travel time reliability and to prepare a guidebook that practitioners and others can use to design, build, operate, and maintain such systems. The focus of this project is on travel time reliability, but it is important to be aware that traffic detectors acquire data not directly related to travel time reliability, including operations, pavement design, safety analysis, and security. The data from the monitoring system(s) developed in this project—from both public and private sources—should include, wherever cost-effective, information on the seven sources of nonrecurring congestion. Data from the travel time reliability monitoring system(s) can then be used to construct performance measures or to perform various analyses useful for real-time operations management as well as policy, planning, and programming, especially exploring trade-offs between capital and operations expenditures.	http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=2178, accessed 12/7/2010

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TABLE A.1 ADDITIONAL RESOURCES (continued)

ID	Subject	Title/Date	Description	Reference/URL
7.	Performance Measurement	A Framework for Improving Travel Time Reliability, SHRP 2 Project L14, active (estimated February 2012)	The objectives of SHRP 2 Project L14 are to provide a means to incorporate SHRP 2 reliability research findings and products into mainstream practice; develop a simple, easy to understand definition for travel time reliability; explain the value and importance of reliability and operations; and develop a synthesis and online knowledge transfer system on reliability.	http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2649, accessed 12/14/2010
8.	Analysis Tools	Operations Benefit/Cost Analysis Desk Reference, active (estimated September 2011)	This project will develop a reference guide and decision support tool for practitioners looking to estimate the impacts, benefits, and costs of intelligent transportation systems (ITS) and operational improvements. The reference guide will summarize existing B/C tools and methods available and suggest approaches to promote more consistent application of available tools.	http://ops.fhwa.dot.gov/index.asp, accessed 12/13/2010
9.	Analysis Tools	FHWA Traffic Analysis Tools Program	The Traffic Analysis Tools Program provides guidance on the selection and use of traffic analysis tools and innovative approaches that consider a system-level approach for enhancing mobility. The program was formulated by FHWA in an attempt to strike a balance between efforts to develop new, improved analysis tools in support of traffic operations analysis and efforts to facilitate the deployment and use of existing analysis tools. This resource contains 10 current volumes on topics such as traffic analysis tools primer, decision support methodology for selecting tools, guidelines for applying various tools, calculating measures of effectiveness, and predicting performance.	http://ops.fhwa.dot.gov/trafficanalysistools/index.htm, accessed 12/13/2010

(continued)

TABLE A.1 ADDITIONAL RESOURCES (continued)

ID	Subject	Title/Date	Description	Reference/URL
10.	Analysis Tools	Intelligent Transportation Systems Benefits, Costs, and Lessons Learned: 2005 Update	Intelligent Transportation Systems Benefits, Costs, and Lessons Learned: 2005 Update is the sixth in a series of periodic publications that began in 1995. It is the next step toward a vision of one-stop shopping for qualitative and quantitative information about ITS. As a public service, DOT sponsors regularly updated ITS Benefits and Costs Databases available online at www.benefitcost.its.dot.gov, which provide delay adjustment factors for operational improvements. Companion web sites documenting the amount and geographical deployment of ITS and the Lessons Learned Database, which is scheduled to be online in the summer of 2005, can be accessed online through the ITS Joint Program Office's homepage at www.its.dot.gov	http://www.itsdocs.fhwa.dot.gov/JPODOCS/REPTS_TE/14073.htm, accessed 12/6/2010
11.	Analysis Tools	ITS Deployment Analysis System (IDAS) web site and User's Manual	The ITS Deployment Analysis System (IDAS) is designed to assist agencies in integrating ITS in the transportation planning process. IDAS allows users to conduct a systematic assessment of the benefits and costs of various ITS deployments through the following capabilities: comparison and screening of ITS alternatives; estimation of impacts and traveler responses to ITS; estimation of life-cycle costs; inventory of ITS equipment and identification of cost-sharing opportunities; sensitivity and risk analysis; ITS deployment and operations/maintenance scheduling; and documentation for transition into design and implementation.	http://idas.camsys.com/, accessed 12/7/2010
12.	Analysis Tools	Highway Economic Requirements System (HERS) Program and User's Guide, December 2006	The Highway Economic Requirements System (HERS) is a software package that predicts the investment required to achieve certain highway system performance levels. Alternatively, the software can be used to estimate the highway system performance that would result given various investment levels. HERS currently models the effects of ITS and operations strategies on highway investment and performance based on preprocessed, externally defined deployment trends.	http://www.fhwa.dot.gov/infrastructure/asstmgmt/hersindex.cfm, accessed 12/15/2010
13.	Analysis Tools	SCReening for ITS (SCRITS) Spreadsheet and User's Guide, January 1999	SCReening for ITS (SCRITS) is a spreadsheet analysis tool for estimating the user benefits of ITS. It is a sketch-level or screening-level analysis tool that allows practitioners to obtain an initial indication of the possible benefits of various ITS applications.	http://www.fhwa.dot.gov/steam/scrits.htm, accessed 12/15/2010

(continued)

TABLE A.1 ADDITIONAL RESOURCES (continued)

ID	Subject	Title/Date	Description	Reference/URL
14.	Analysis Tools	U.S. DOT Integrated Corridor Management Program	With ICM, various institutional partner agencies manage the transportation corridor as a system, rather than the more traditional approach of managing individual assets. A corridor is managed as an integrated asset in order to improve travel time reliability and predictability, help manage congestion, and empower travelers through better information and more choices. In an ICM corridor, because of proactive multimodal management of infrastructure assets by institutional partners, travelers could receive information that encompasses the entire transportation network. They could dynamically shift to alternative transportation options—even during a trip—in response to changing traffic conditions. The ICM Knowledgebase includes detailed documentation on ICM concepts of operations; the Analysis, Modeling, and Simulation methodology; tools used for modeling and simulation; and resulting impacts on corridor performance.	http://www.its.dot.gov/icms/resources/view_all.cfm, accessed 12/14/2010
15.	Analysis Tools	Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies, SHRP 2 L03, October 2009	The objective of SHRP 2 Project L03 was to develop predictive relationships for reliability as a function of highway, traffic, and operating conditions. The analysis approach included foundational research on reliability concepts and the types of improvement strategies that affect travel time reliability; before/after analysis to assess impacts of improvement strategies on reliability; cross-sectional statistical modeling to assess reliability as a function of volume, capacity and disruptions; and an analysis of congestion by source. The research found that one of the key metrics of reliability, the 95th percentile travel time, can be predicted from the mean travel time.	http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=2179, accessed 12/13/2010

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TABLE A.1 ADDITIONAL RESOURCES (continued)

ID	Subject	Title/Date	Description	Reference/URL
16.	Analysis Tools	Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools, SHRP 2 L04, active (estimated February 2012)	The objective of SHRP 2 Project L04 is to develop the capability to produce measures of reliability performance as output in traffic simulation models and planning models, and to determine how travel demand forecasting models can use reliability measures to produce revised estimates of travel patterns.	http://www.trb.org/TRBNet/ProjectDisplay.asp?ProjectID=2193, accessed 12/13/2010
17.	Analysis Tools	Evaluating Alternative Operations Strategies to Improve Travel Time Reliability, SHRP 2 L11, April 2010	The objective of SHRP 2 Project L11 is to identify and evaluate strategies and tactics to satisfy the travel time reliability requirements of users of the roadway network, including freight and person transport in urban and rural areas.	http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2192, accessed 12/14/2010
18.	Planning Process	Statewide Opportunities for Integrating Operations, Safety, and Multimodal Planning: A Reference Manual, May 2010	This reference manual is designed to assist state DOTs, MPOs and local agencies in integrating operations, safety, and multimodal planning activities. It identifies specific opportunities for integration at various levels of decision making, including the statewide, regional, corridor, and project levels, and the associated challenges and benefits of these approaches. Case study examples, toolkits, and a self-assessment checklist are also provided.	http://www.fhwa.dot.gov/planning/statewide/manual/manual.pdf, accessed 12/13/2010

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TABLE A.1 ADDITIONAL RESOURCES (continued)

ID	Subject	Title/Date	Description	Reference/URL
19.	Planning Process	Advancing Metropolitan Planning for Operations: An Objectives-Driven, Performance-Based Approach—A Guidebook, February 2010	This guide is designed to help metropolitan planning organizations (MPOs) and other stakeholders in the metropolitan transportation planning process to create an objectives-driven, performance-oriented transportation plan which not only meets SAFETEALU requirements for M&O but results in a metropolitan transportation plan (MTP) that is better able to meet customer needs, resulting in an optimal mix of transportation investments between capacity and operational strategies. The guide includes a systematic process for developing performance measures, assessing needs, selecting strategies, and performing ongoing monitoring and evaluation; information on engaging stakeholders; steps for getting started with the approach; and a self-assessment tool for integrating the congestion management process into the MTP.	http://ops.fhwa.dot.gov/publications/fhwahop10026/fhwa_hop_10_026.pdf, accessed 12/14/2010
20.	Planning Process	Advancing Metropolitan Planning for Operations: The Building Blocks of a Model Transportation Plan Incorporating Operations—A Desk Reference, April 2010	The Desk Reference is a resource designed to enable planners to begin incorporating outcomes-oriented operations into the metropolitan planning process. The "toolbox" includes types of possible operations objectives, with associated performance measures, data needs, and strategies that regions can utilize as a starting point toward advancing Planning for Operations in their area. It includes a model metropolitan transportation plan with commentary to illustrate the results of an objectives-driven, performance-based approach to planning for operations.	http://ops.fhwa.dot.gov/publications/fhwahop10027/fhwahop10027.pdf, accessed 12/14/2010

(continued)

TABLE A.1 ADDITIONAL RESOURCES (continued)

ID	Subject	Title/Date	Description	Reference/URL
21.	Planning Process	An Interim Guidebook on the Congestion Management Process in Metropolitan Transportation Planning, February 2008	This guide is designed to help metropolitan planning organizations (MPO) to create an objectives-driven, performance-based congestion management process that meets SAFETEA-LU requirements for Transportation Management Areas. The guidebook includes a discussion of objectives-driven, performance-based planning and the characteristics of the CMP; the Basics of CMP, including defining seven steps to developing a CMP; Development and Implementation of an Objectives-Driven CMP, which provides information about getting started in the development of the CMP, either building such a process from the ground up or adapting existing systems and procedures; and information about how the CMP can provide a link to the environmental review process, as well as other potential applications of the CMP approach. Also included is a self-assessment tool that can provide a perspective on where an MPO stands in implementing the CMP. Appendices provide a glossary of useful terms and references to other resources.	http://www.ops.fhwa.dot.gov/publications/cmpguidebook/cmpguidebook.pdf, accessed 12/13/2010
22.	Planning Process	A Framework for Collaborative Decision Making on Additions to Highway Capacity, SHRP 2 C01, active (estimated March 2012)	The SHRP 2 C01 project is developing an integrated and consistent planning and programming process as part of the Collaborative Decision-Making Framework (CDMF). The C01 project identifies key decision points that need to be consistent and connected in these processes, while the C02 project (below) provides performance measures that can help bind decision making together. Successful integration of reliability will certainly benefit from an improved planning and programming process as envisioned in the CDMF, but the CDMF will likely not be implemented widely in a short period. Some transportation agencies may never have a fully collaborative decision-making process and yet will still be able to better integrate reliability into the planning and programming processes. The resulting handbook will be useful for agencies at different stages of integration.	http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2161, accessed 12/14/2010

(continued)

TABLE A.1 ADDITIONAL RESOURCES (continued)

ID	Subject	Title/Date	Description	Reference/URL
23.	Planning Process	A Systems-Based Performance Measurement Framework for Highway Capacity Decision Making, SHRP 2 C02, October 2009	The SHRP 2 C02 project is developing a performance measurement framework that informs a collaborative decision-making process. The measures reflect mobility, accessibility, economic, safety, environmental, watershed, habitat, community, and social considerations. A web-based library links performance measures to key decision points in the transportation project planning process.	http://apps.trb.org/cmsfeed/TRBNetProjectDisplay.asp?ProjectID=2184, accessed 12/14/2010
24.	Planning Process	PlanWorks (formerly known as TCAPP) web site	The PlanWorks (formerly known as TCAPP) web site was created to enhance collaboration in the transportation decision-making process. The web site includes a collaboration assessment, a decision guide for various phases of transportation decision making, practical applications, and case study examples. The web site also includes the performance measures library developed in SHRP 2 Project C02 and will eventually house all SHRP 2 Capacity research products.	http://www.transportationforcommunities.com/, accessed 12/14/2010

TABLE A.2 REFERENCE TO OTHER SHRP 2 PROJECTS

SHRP 2 Project	SHRP 2 Project Purpose and Outcomes	Tools for Reliability	Reference in L05 Documents
L01: Integrating Business Processes to Improve Reliability—complete	The objective of this project was to identify and report on successful practices that integrate business processes to improve travel time reliability. These business processes concern operations and related activities, such as the actions to address the flooding of a highway and actions taken to provide traveler information regarding congestion and unsafe road conditions. The research also addressed strategies that integrate business processes concerning the seven major sources of unreliability that affect nonrecurrent congestion. Project L01 inferred from a series of case studies how various business processes contributed to improving travel time reliability and the extent the business processes informed one another.	N/A	Technical Reference Chapters 2 and 3
L02: Establishing Monitoring Programs for Mobility and Travel Time Reliability—complete	Project L02 was conducted to create methods by which travel time reliability can be monitored, assessed, and communicated to end users of the transportation system. The project developed guidance for operating agencies about how they can put reliability measurement methods into practice by enhancing existing monitoring systems or creating new ones. The project's main product is a guidebook that describes how to develop and use a Travel Time Reliability Monitoring System (TTRMS). L02 focused on how to measure reliability, how to understand what makes a system unreliable, and how to pinpoint mitigating actions. The TTRMS analysis methods will let managers know if and how traffic incidents, weather, and other nonrecurring events affect reliability, and the extent of the effect.	L02 analysis methods for assessing the reliability impacts of traffic incidents, weather, and other nonrecurring events	Guide Chapters 2, 4, and 6 Technical Reference Chapters 2, 3, and 5
L03: Analytic Procedures for Determining the Impacts of Reliability Mitigation Strategies—complete	The objective of the L03 project was to develop technical relationships between reliability improvement strategies and reliability performance metrics. This project defined reliability, explained the importance of travel time distributions for measuring reliability, and recommended specific reliability performance measures. This study reexamined the contribution of the various causes of nonrecurring congestion. Numerous actions that can potentially reduce nonrecurring congestion were identified with an indication of their relative importance. Models for predicting nonrecurring congestion were developed using three methods, all based on empirical procedures: The first involved before and after studies; the second was termed a "data-poor" approach and resulted in a parsimonious and easy-to-apply set of models; the third was entitled a "data-rich model" and used cross-section inputs including data on selected factors known to directly affect nonrecurring congestion.	L03 reliability prediction equations based on "data-poor" and "data-rich" models	Guide Chapters 2 and 4 Technical Reference Chapters 1, 2, 3, 5, and 6, and Appendix B.

(continued)

TABLE A.2 REFERENCE TO OTHER SHRP 2 PROJECTS (continued)

SHRP 2 Project	SHRP 2 Project Purpose and Outcomes	Tools for Reliability	Reference in L05 Documents
L04: Incorporating Reliability Performance Measures in Operations and Planning Modeling Tools—under way	The objectives of this project are to (1) develop the capability of producing measures of reliability performance as output in traffic simulation models and planning models, and (2) determine how travel demand forecasting models can use reliability measures to produce revised estimates of travel patterns. Recent research evidence suggests that travel time reliability is an element of a traveler's choice of departure time, route, mode, and perhaps whether to travel at all. This implies that traffic conditions influence the demand for and nature of travel. In order to make traffic patterns and travel demand forecasting sensitive to traffic conditions, there is a need to develop the underlying relationships between travel time reliability and travel demand and to upgrade analysis and forecasting tools accordingly. A new generation of models and computer analysis offers the potential, but the techniques have yet to be developed. The emphasis in Project L04 is on improving traffic operations and planning models to reflect travel time reliability and generate travel time reliability as a model output.	L04 pre-processor (Simulation Manager) and post-processor (Trajectory Processor), which input and extract various reliability performance measures from simulation output	Guide Chapter 5 Technical Reference Chapters 2 and 3
L06: Institutional Architectures to Advance Operational Strategies—complete	The objective of Project L06 was to undertake a comprehensive and systematic examination of the way agencies should be organized to successfully execute operations programs that improve travel time reliability. The project elements included • Addressing key issues involved in creating an improved institutional architecture (organizational structures, policies, procedures, relationships, etc.) that supports and manages operational activities that can improve travel time reliability. • Identifying and assessing the institutional changes exemplary state DOTs and other metropolitan transportation agencies have made in order to organize and adapt to focus on improved travel time reliability. • Identifying and assessing the institutional structures, policies, procedures, and relationships adopted by nontransportation organizations that deliver public sector infrastructure or services aimed at improving service delivery.	N/A	Technical Reference Chapters 2, 3, and 7

(continued)

TABLE A.2 REFERENCE TO OTHER SHRP 2 PROJECTS (continued)

SHRP 2 Project	SHRP 2 Project Purpose and Outcomes	Tools for Reliability	Reference in L05 Documents
L07: Evaluation of Cost-Effectiveness of Highway Design Features—under way	The objective of the L07 project is to identify the full range of possible roadway design features used by transportation agencies on freeways and major arterials to improve travel time reliability; assess their costs, operational effectiveness, and safety; and provide recommendations for their use and eventual incorporation into appropriate design guides. The project will address geometric design requirements and application; an understanding of how specific conditions affect design and operation of highway systems; alternative economic analysis techniques; and how operational effectiveness and safety are measured and estimated. Where existing effectiveness analysis methods are inadequate, alternative approaches will be needed to generate useful results.	L07 hybrid method combining microsimulation with the L03 data-rich reliability prediction equations	Technical Reference Chapters 2, 3, and 5
L08: Incorporation of Travel Time Reliability into the Highway Capacity Manual—under way	The objective of this project is to determine how data and information on the impacts of differing causes of nonrecurrent congestion (incidents, weather, work zones, special events, etc.) in the context of highway capacity can be incorporated into the performance measure estimation procedures contained in the HCM. The methodologies contained in the HCM for predicting delay, speed, queuing, and other performance measures for alternative highway designs are not currently sensitive to traffic management techniques and other operation/design measures for reducing nonrecurrent congestion. A further objective is to develop methodologies to predict travel time reliability on selected types of facilities and within corridors, specifically • Develop travel time reliability as a performance measure in the HCM for freeway facilities; • Develop travel time reliability as a performance measure in the HCM for urban street facilities; and • Address freeway and urban streets in a corridor context.	L08 FREEVAL and STREETVAL tools that combine multiscenario methods with traffic flow models to determine reliability of freeways and urban streets; multiscenario generator	Technical Reference Chapters 2 and 3

(continued)

TABLE A.2 REFERENCE TO OTHER SHRP 2 PROJECTS (continued)

SHRP 2 Project	SHRP 2 Project Purpose and Outcomes	Tools for Reliability	Reference in L05 Documents
L11: Evaluating Alternative Operations Strategies to Improve Travel Time Reliability—complete	The objective of this project was to identify and evaluate strategies and tactics for satisfying the travel time reliability requirements of users of the roadway network—those engaged in both freight and person transport in urban and rural areas. These strategies needed to serve the near and more distant future and incorporate current and innovative approaches, both low tech and high tech. Many technological changes, operational solutions, and organizational actions for improving travel time reliability exist now, and even more will become available in the next 20 years. These changes, solutions, and actions can provide more effective management of transportation demand, increases in person- and freight-moving capacity, and faster recovery of the capacity lost to various types of disruptions.	L11 approach for valuing reliability based on options theory	Technical Reference Chapters 2 and 3
L14: Traveler Information and Travel Time Reliability—under way	The L14 project has multiple objectives, which are to • Better understand the current and near-term future dimensions of the travel time/travel reliability information marketplace, including technologies, the roles of the public and private sectors, and choices (both free and priced) available to travelers. • Better understand what network travel time and travel reliability information travelers require, and better understand how travelers would use improved information. • Determine how best to communicate travel time reliability information to travelers so that they can understand it and use it to make optimal travel choices, and develop a guide to help providers ensure that information regarding travel time reliability is offered in a manner that is most useful to travelers. • Develop a simple and standardizable lexicon for communicating travel time reliability concepts among transportation professionals and travelers. • Develop prioritized, near-term strategies for improved dissemination of travel time reliability information and provide guidance for public sector transportation agencies that may provide travel reliability information to travelers.	L14 lexicon for communicating travel time reliability concepts	Guide Chapter 2 Technical Reference Chapter 3

(continued)

TABLE A.2 REFERENCE TO OTHER SHRP 2 PROJECTS (continued)

SHRP 2 Project	SHRP 2 Project Purpose and Outcomes	Tools for Reliability	Reference in L05 Documents
C01: A Framework for Collaborative Decision Making on Additions to Highway Capacity—under way	The objectives of the C01 project are to develop a systems-based, transparent, well-defined framework for consistently reaching collaborative decisions on transportation capacity enhancements and identify a SHRP 2 research strategy for addressing gaps in supporting information systems. The project will • Identify key decision points in the project approval process; • Identify the elements common to successful outcomes, and prepare insightful case studies from which others can learn; • Identify the critical barriers to a better analytical process, grounded in the principals of environmental stewardship, for screening transportation solutions; • Recommend products appropriate for SHRP 2 that will have maximum positive impact on the state of the practice; and • Develop a framework or frameworks to support collaborative decision making in transportation that address system-level integration of transportation, protection of the human and natural environment, land development policy, and economic development strategies.	N/A	Technical Reference Chapter 3
C02: A Systems-Based Performance Measurement Framework for Highway Capacity Decision Making—complete	The objective the C02 project was to develop a performance measurement framework that informs a collaborative decision-making process. The measures reflect mobility, accessibility, economic, safety, environmental, watershed, habitat, community, and social considerations.	C02 performance measurement framework	Guide Chapter 5
C03: Interactions between Transportation Capacity, Economic Systems, and Land Use merged with Integrating Economic Considerations Project Development—complete	This project had three objectives: (1) to provide a resource to help determine the net changes in the economic systems of an area impacted by a transportation capacity investment; (2) to provide data and results from enough structured cases that project planners in the future can use the cases to demonstrate by analogy the likely impacts of a proposed project or group of projects (plan); and (3) to demonstrate how this fits into collaborative decision making for capacity expansion.	N/A	Technical Reference Chapter 3

(continued)

TABLE A.2 REFERENCE TO OTHER SHRP 2 PROJECTS (continued)

SHRP 2 Project	SHRP 2 Project Purpose and Outcomes	Tools for Reliability	Reference in L05 Documents
C04: Improving Our Understanding of How Highway Congestion and Pricing Affect Travel Demand—complete	The objective of the C04 project was to develop mathematical descriptions of the full range of highway user behavioral responses to congestion, travel time reliability, and pricing. This included formatting the mathematical descriptions of behavior so that they could be incorporated into various travel demand modeling systems in use or being developed. Another objective was to examine network assignment practices needed to support models that simulate behavioral responses to congestion, travel time reliability, and pricing.	C04 highway utility model that incorporates behavioral response to congestion, travel time, and cost.	Guide Chapter 5 Technical Reference Chapters 2 and 6
C05: Understanding the Contribution of Operations, Technology, and Design to Meeting Highway Capacity Needs—complete	This project had three objectives: (1) quantify the capacity benefits—individually and cooperatively—of operations, design, and technology improvements at the network level for both new and existing facilities; (2) provide transportation planners with the information and tools to analyze operational improvements as an alternative to traditional construction (for example, determining what operational improvements will give the same capacity gain as an additional lane); and (3) develop guidelines for sustained service rates to be used in planning networks for limited access highways and urban arterials.	C05 enhanced Dynamic Traffic Assignment (DTA) modeling tools; new link, corridor, and network diagnostic tools; methodology for analyzing operational improvements	Technical Reference Chapters 2 and 5
C10: Partnership to Develop an Integrated, Advanced Travel Demand Model and a Fine-Grained, Time-Sensitive Network—under way	The goal of Project C10 is to improve modeling and network processes and procedures in order to address policy and investment questions that cannot be well addressed now, and to facilitate further development, deployment, and application of these procedures. The primary objective of this project is to make operational in two public agencies a dynamic integrated model and an integrated, advanced travel-demand model with a fine-grained, time-dependent network (integrated activities and networks).	C10 open source dynamic integrated model	Technical Reference Chapter 3
C11: Development of Improved Economic Analysis Tools Based on Recommendations from Project C03—under way	The main objective of C11 will be to statistically examine the relationships among variables in the C03 case study dataset and to develop a suite of straightforward, transparent, and useful open source statistical forecasting models/tools that function at a level between the C03 case study-based web tool (which is essentially descriptive in nature) and more complex, economic impact assessment models/tools such as IMPLAN and REMI.	C11 open source statistical forecasting models/tools	Technical Reference Chapter 3

B

TRENDS IN RELIABILITY

The SHRP 2 L03 report, *Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies*, provides an illustrative example of the challenges in interpreting the varied results of a reliability analysis. The section, Trends in Reliability, is excerpted in this appendix.

SHRP 2 L03 Excerpt

An examination of congestion and reliability trends from 2006 to 2008 on the 10 Atlanta study sections was undertaken. Anecdotal information suggested that congestion had decreased in 2008 after a midyear spike in gas prices midyear and the economic downturn. Table B.1 presents the results for the peak period. Note that the peak period was fixed and was determined using the procedure given in Section 4.6 using 2006 data. On all 10 sections, the TTI increased between 2006 and 2007 and decreased between 2007 and 2008. In nine cases, the 2008 TTIs were below those of 2006. Note that eight of the 10 sections had ramp meters installed in 2008.

On seven of the 10 study sections, the buffer index actually increased in 2008 over 2007 levels, yet overall congestion was better (i.e., TTI went down). The two components of the buffer index (95th percentile and mean travel time) decreased in all cases. However, when the buffer index increased, it can be seen that the drop in the 95th percentile was proportionately lower than the drop in the mean travel time, leading to a higher index value. The 80th percentile travel time decreased in 2008 on all sections, and the skew statistic exhibits a similar pattern as the buffer index. The planning time index [not shown in the table] exhibited the same characteristics as the 95th percentile since its base is free-flow speed, which does not change.

Figures B.1 and B.2 show the travel time distributions for two sections where the buffer index and skew statistic increased.

TABLE B.1. TRENDS IN RELIABILITY, ATLANTA FREEWAYS (2006–2008)

Section/Reliability Measure	Year 2006	2007	2008
SHRP Section I-75 Northbound from I-285 to Roswell Road			
Travel Time Index (TTI)	2.046	2.026	1.665
Average TTI	11.271	11.162	9.177
95th Percentile TTI	16.934	17.507	14.800
Buffer Index	0.502	0.568	0.613
80th Percentile TTI	13.974	14.191	11.458
Skew Statistic	0.942	1.087	1.514
Daily VMT	691,399	689,628	N/A
SHRP Section I-75 Southbound from I-285 to Roswell Road			
TTI	1.312	1.369	1.293
Average TTI	7.665	7.994	7.552
95th Percentile TTI	10.139	10.517	9.868
Buffer Index	0.323	0.316	0.307
80th Percentile TTI	8.353	8.719	8.306
Skew Statistic	1.524	1.515	1.461
Daily VMT	691,399	689,628	N/A
SHRP Section I-75 Northbound from I-20 to Brookwood			
TTI	1.350	1.542	1.339
Average TTI	6.710	7.664	6.656
95th Percentile TTI	8.120	10.755	8.031
Buffer Index	0.210	0.403	0.207
80th Percentile TTI	7.097	8.112	7.015
Skew Statistic	1.283	1.923	0.771
Daily VMT	616,038	620,959	595,034
SHRP Section I-75 Southbound from I-20 to Brookwood			
TTI	2.052	2.171	2.067
Average TTI	9.336	9.877	9.404
95th Percentile TTI	13.110	14.270	12.389
Buffer Index	0.404	0.445	0.317
80th Percentile TTI	10.805	11.416	11.042
Skew Statistic	1.324	1.120	0.956
Daily VMT	616,038	620,959	595,034

(continued)

TABLE B.1. TRENDS IN RELIABILITY, ATLANTA FREEWAYS (2006–2008) (continued)

Section/Reliability Measure	Year		
	2006	2007	2008
SHRP Section I-285 Eastbound from GA 400 to I-75			
TTI	1.359	1.481	1.380
Average TTI	9.322	10.162	9.469
95th Percentile TTI	12.548	13.150	12.493
Buffer Index	0.346	0.294	0.319
80th Percentile TTI	10.505	11.382	10.849
Skew Statistic	1.148	0.996	1.070
Daily VMT	584,487	588,442	572,211
SHRP Section I-285 Westbound from GA 400 to I-75			
TTI	1.826	1.893	1.672
Average TTI	12.564	13.026	11.504
95th Percentile TTI	19.053	19.754	19.543
Buffer Index	0.517	0.516	0.699
80th Percentile TTI	15.632	16.140	14.699
Skew Statistic	1.202	1.043	1.779
Daily VMT	584,487	588,442	572,211
SHRP Section I-285 Eastbound from GA 400 to I-85			
TTI	2.247	2.314	1.797
Average TTI	14.495	14.926	11.593
95th Percentile TTI	23.353	24.724	21.084
Buffer Index	0.611	0.656	0.819
80th Percentile TTI	19.336	19.945	15.256
Skew Statistic	1.285	1.248	2.347
Daily VMT	588,597	580,629	567,497
SHRP Section I-285 Westbound from GA 400 to I-85			
TTI	1.621	1.681	1.511
Average TTI	10.424	10.809	9.713
95th Percentile TTI	13.740	13.707	12.612
Buffer Index	0.318	0.268	0.299
80th Percentile TTI	11.622	11.957	11.082
Skew Statistic	0.790	0.763	0.656
Daily VMT	588,597	580,629	567,497

(continued)

TABLE B.1. TRENDS IN RELIABILITY, ATLANTA FREEWAYS (2006–2008) (continued)

Section/Reliability Measure	Year 2006	2007	2008
SHRP Section I-75 Northbound from Roswell Road to Barrett Parkway			
TTI	1.579	1.652	1.514
Average TTI	8.762	9.170	8.405
95th Percentile TTI	11.827	12.823	12.357
Buffer Index	0.350	0.398	0.470
80th Percentile TTI	10.206	10.560	9.656
Skew Statistic	1.513	1.348	1.586
Daily VMT	669,568	675,274	N/A
SHRP Section I-75 Southbound from Roswell Road to Barrett Parkway			
TTI	1.809	1.872	1.614
Average TTI	9.785	10.129	8.730
95th Percentile TTI	13.835	14.301	12.791
Buffer Index	0.414	0.412	0.465
80th Percentile TTI	11.208	11.575	10.529
Skew Statistic	0.849	0.920	0.945
Daily VMT	669,568	675,274	N/A
All Sections			
TTI	1.720	1.800	1.585
Average TTI	10.033	10.492	9.220
95th Percentile TTI	14.266	15.151	13.597
Buffer Index	0.399	0.428	0.451
80th Percentile TTI	11.874	12.400	10.989
Skew Statistic	1.186	1.196	1.308
Daily VMT	3,150,088	3,154,932	2,878,074
Daily VMT without I-75 (I-285 to Barrett Pkwy)	1,789,122	1,790,030	1,734,742

Source: Cambridge Systematics, Inc. *SHRP 2 Report S2-L03-RR-1: Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies.* Transportation Research Board, Washington, D.C., February 2010.

- The I-75 section had ramp meters turned on in mid-October 2008 and saw a decrease in demand of 5.5% from 2007 to 2008; and
- The I-285 section had ramp meters turned on by July 1, 2008, and saw a decrease in demand of 1.8%.

Note that for the same fixed peak period, there was more free-flow travel in 2008 on both sections. On the I-75 section the increase in free-flow travel was due primarily to the decrease in demand, but on the I-85 section the improved flow was probably due to a combination of reduced demand and ramp meters. Both the buffer index and the

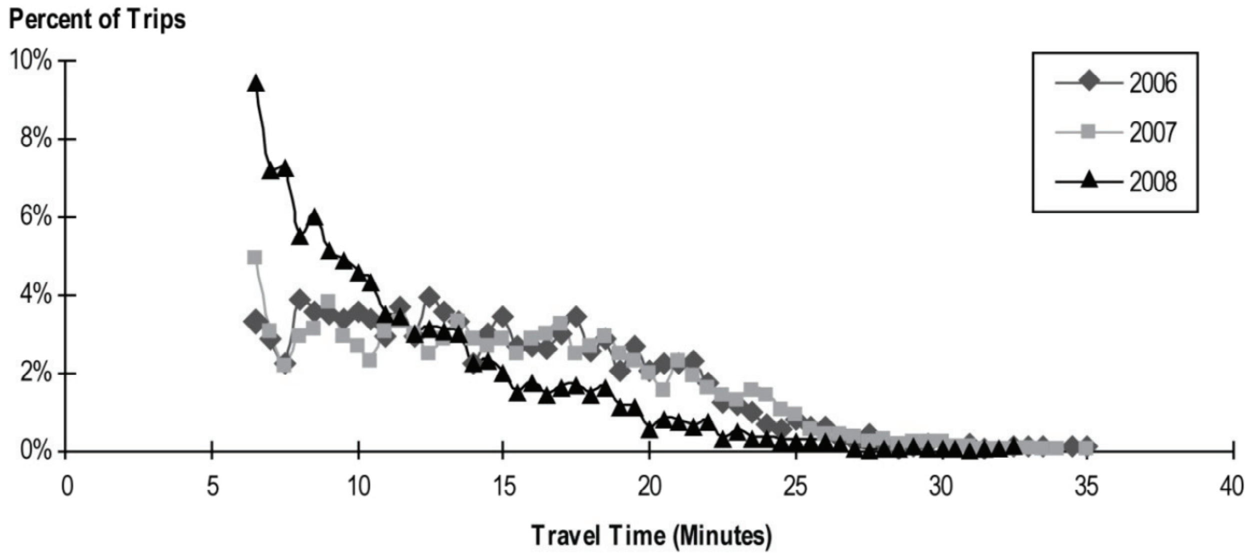

Figure B.1 *I-285 eastbound. GA 400 to I-85, Peak Period*
Source: Cambridge Systematics, Inc. *SHRP 2 Report* S2-L03-RR-1: *Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies.* Transportation Research Board, Washington, D.C., February 2010.

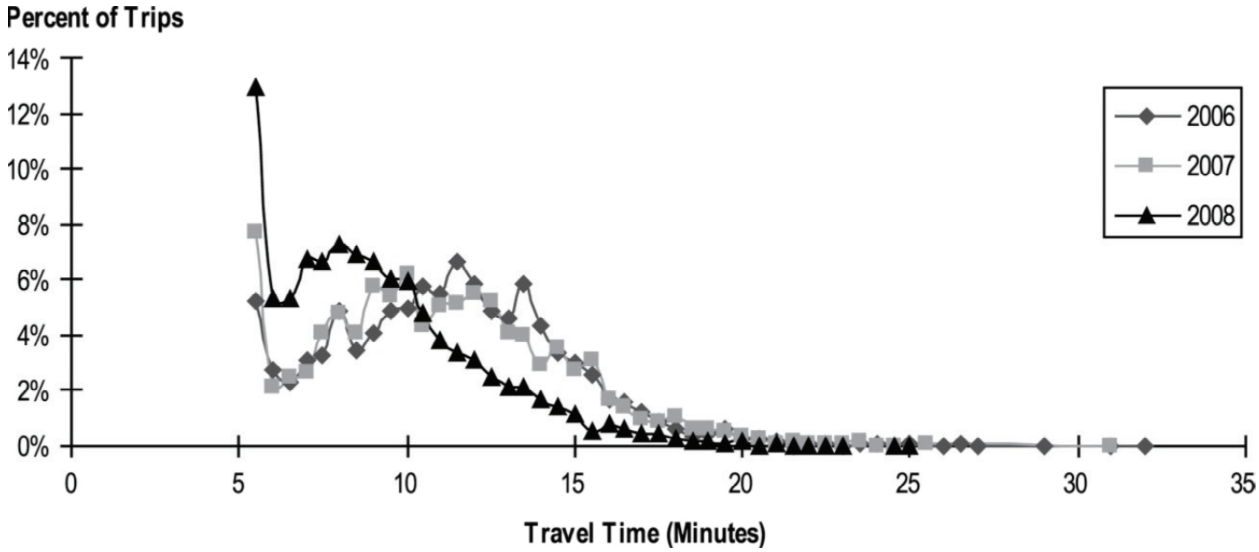

Figure B.2 *I-75 northbound. I-285 to Roswell Road, Peak Period*
Source: Cambridge Systematics, Inc. *SHRP 2 Report* S2-L03-RR-1: *Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies.* Transportation Research Board, Washington, D.C., February 2010.

skew statistic indicate there was more spread in the distribution, but the worst travel times (the 80th and 95th percentiles) were decreased. [Anecdotal information suggested that congestion had decreased in 2008 after a midyear spike in gas prices and the economic downturn.]

Both the buffer index and the skew statistic indicate there was more spread in the distribution, but the worst travel times (the 80th and 95th percentiles) were decreased. That the drop in the 95th percentile was not as great as the drop in the mean indicates that although base (typical) conditions improved, the variation around the new base was higher (as indicated by the buffer index and skew statistic). So, for a traveler in 2008, the worst days are better than they were in 2007, but compared with a typical trip, the worst days are proportionately worse. Whether reliability got better or worse depends on whether the traveler perceives the extra time in absolute or relative terms. In absolute terms, the buffer time (95th percentile minus the mean) improved in 2008.

Assume for the moment that the decreases in the metrics are due solely to the decreased demand in 2008, which would have reduced base (recurring) congestion. Also assume that the worst travel times are influenced by roadway events such as incidents. The decreases in the 80th and 95th percentiles in 2008 are another indication of the interaction between base congestion and events; that is, assuming event characteristics are equivalent, less base congestion leads to lower event-related congestion. However, the lessened impact is somewhat marginal; the drop in the worst travel times was not as big as for base congestion.

There are two implications of these results for future research and existing practice. First, the buffer index may not be the most appropriate metric for tracking trends. In the Atlanta analysis, it can be seen that the mean travel times had a proportionately higher decrease than the 95th percentile. Presumably, this trend occurred because the major factor was decreased demand, which would tend to decrease all travel times, and not primarily affect the extremes as some operational treatments do. So, because of the way the buffer index is normalized by the mean, it can produce a counterintuitive result; that is, it can produce worsened reliability and decreased average congestion. Although this nuance means that the buffer index might not be the best metric for measuring trends, it still tells us something useful about conditions. In the new reality of 2008, the size of the buffer did indeed increase, even if the increase was primarily the result of a large decrease in the mean travel time.

The second implication is that demand can have a significant effect on both average congestion level and reliability. Conceptually, demand and base capacity interact with events to produce total congestion patterns. Overall, analysis shows just how important volume is to the congestion and reliability when capacity is improved.

C

IDAS TRAVEL TIME RELIABILITY RATES

TABLE C.1 TRAVEL TIME RELIABILITY: RATES FOR 1-H PEAK—VEHICLE-HOURS OF INCIDENT DELAY PER VEHICLE-MILE

Volume/1-h Level of Service Capacity	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	0.01986	0.01744	0.01368

TABLE C.2 TRAVEL TIME RELIABILITY: RATES FOR 2-H PEAK PERIOD—VEHICLE-HOURS OF INCIDENT DELAY PER VEHICLE-MILE

Volume/1-h Level of Service Capacity	Number of Lanes		
	2	3	4+
0.1	3.53E-08	1.50E-09	4.74E-12
0.2	5.38E-07	4.83E-08	6.28E-10
0.3	2.65E-06	3.68E-07	1.10E-08
0.4	8.20E-06	1.56E-06	8.32E-08
0.5	1.97E-05	4.76E-06	4.01E-07
0.6	4.04E-05	1.19E-05	1.45E-06
0.7	7.40E-05	2.57E-05	4.30E-06
0.8	0.000125	5.01E-05	1.10E-05
0.9	0.000199	9.04E-05	2.53E-05
1	0.000301	0.000153	5.32E-05
1.1	0.000437	0.000247	1.04E-04
1.2	0.000617	0.000382	0.000192
1.3	0.00085	0.000572	0.000338
1.4	0.001158	0.000835	0.00057
1.5	0.001588	0.001206	0.000929
1.6	0.002272	0.001772	0.001477
1.7	0.003558	0.002795	0.002349
1.8	0.006346	0.005087	0.004034
1.9	0.012866	0.011077	0.008786
2	0.01986	0.01744	0.01368

TABLE C.3 TRAVEL TIME RELIABILITY: RATES FOR 3-H PEAK PERIOD—VEHICLE-HOURS OF INCIDENT DELAY PER VEHICLE-MILE

Volume/1-h Level of Service Capacity	Number of Lanes		
	2	3	4+
0.15	3.71E-08	1.62E-09	5.45E-12
0.3	5.66E-07	5.21E-08	7.22E-10
0.45	2.79E-06	3.97E-07	1.26E-08
0.6	8.63E-06	1.68E-06	9.57E-08
0.75	2.07E-05	5.14E-06	4.61E-07
0.9	4.25E-05	1.28E-05	1.67E-06
1.05	7.78E-05	2.77E-05	4.95E-06
1.2	0.000132	5.41E-05	1.27E-05
1.35	0.000209	9.77E-05	2.91E-05
1.5	0.000316	0.000166	6.12E-05
1.65	0.00046	0.000267	0.00012
1.8	0.00065	0.000413	0.000221
1.95	0.000901	0.00062	0.000389
2.1	0.001245	0.000912	0.000656
2.25	0.00177	0.00135	0.001074
2.4	0.002722	0.002115	0.001742
2.55	0.004772	0.003798	0.003011
2.7	0.009674	0.00828	0.006586
2.85	0.014859	0.012966	0.010231
3	0.01986	0.01744	0.01368

TABLE C.4 TRAVEL TIME RELIABILITY: RATES FOR 4-H PEAK PERIOD—VEHICLE-HOURS OF INCIDENT DELAY PER VEHICLE-MILE

Volume/1-h Level of Service Capacity	Number of Lanes		
	2	3	4+
0.2	4.22E-08	1.95E-09	7.44E-12
0.4	6.43E-07	6.28E-08	9.86E-10
0.6	3.16E-06	4.79E-07	1.72E-08
0.8	9.80E-06	2.02E-06	1.31E-07
1	2.36E-05	6.19E-06	6.30E-07
1.2	4.82E-05	1.54E-05	2.28E-06
1.4	8.84E-05	3.34E-05	6.75E-06
1.6	0.000149	6.52E-05	1.73E-05
1.8	0.000237	0.000118	3.97E-05
2	0.000359	0.000199	8.35E-05
2.2	0.000524	0.000322	0.000163
2.4	0.000745	0.000499	0.000302
2.6	0.001052	0.000757	0.000531
2.8	0.00153	0.001152	0.000902
3	0.002431	0.001873	0.001519
3.2	0.004498	0.00359	0.002798
3.4	0.008512	0.007224	0.005687
3.6	0.012546	0.010863	0.008552
3.8	0.01612	0.014113	0.011086
4	0.01986	0.01744	0.01368

TABLE C.5 TRAVEL TIME RELIABILITY: RATES FOR OFF-PEAK OR DAILY—VEHICLE-HOURS OF INCIDENT DELAY PER VEHICLE-MILE

Volume/1-h Level of Service Capacity	Number of Lanes		
	2	3	4+
1	1.17E-07	8.46E-09	8.16E-11
2	1.79E-06	2.73E-07	1.08E-08
3	8.81E-06	2.08E-06	1.89E-07
4	2.73E-05	8.78E-06	1.43E-06
5	6.56E-05	2.69E-05	6.91E-06
6	0.000134	6.70E-05	2.50E-05
7	0.000248	0.000145	7.41E-05
8	0.000434	0.000289	0.00019
9	0.000824	0.000591	0.000447
10	0.00217	0.00171	0.00125
11	0.00355	0.00299	0.00231
12	0.00519	0.00442	0.00344
13	0.00656	0.0056	0.00435
14	0.00837	0.00718	0.00561
15	0.0106	0.00925	0.00727

Note: Volume is factored to daily estimate to generate volume/1-h level of service capacity ratio.

D

BENEFITS AND COSTS OF FULL OPERATIONS AND ITS DEPLOYMENT: TECHNICAL APPENDIX

D.1 BACKGROUND

This technical appendix provides a general overview of the methodology used in the study of the potential benefits of fully deploying operations and ITS strategies. This study was initiated by the U.S. DOT to explore the benefits and costs of fully deploying and integrating ITS and operations strategies in metropolitan areas. Three test sites (Tucson, Arizona; Cincinnati, Ohio; and Seattle, Washington) were selected to represent small, medium, and large metropolitan areas respectively. Hypothetical deployment scenarios were developed to represent the full logical deployment of operations and ITS strategies in each area. These scenarios were then evaluated to identify the likely benefits and costs of the deployments. The goal of this study was to provide transportation professionals and decision makers with an increased understanding of the potential benefits possible through the full deployment of ITS and operations strategies.

The findings from these three case studies are summarized in individual reports. This appendix provides additional detail on the similar approach used in all three regions to estimate the likely benefits and costs of full operations and ITS deployment.

D.2 METHODOLOGY OVERVIEW

The goal of this analysis was to estimate the likely benefits and costs resulting from the full deployment and integration of ITS and operations strategies in a region. For the purpose of this study, “full deployment” is defined as the maximum amount of locally desirable ITS and transportation operations strategies—at the highest range of technical and institutional sophistication—that can be deployed without regard to funding constraints. Consistent with this goal and definition, full operations and ITS deployment scenarios were identified for the three case study regions.

The analysis methodology used in this study was developed to identify the incremental benefits and costs of the strategies contained in the full operations and ITS deployment scenario. To identify these incremental impacts, it was necessary to estimate what travel conditions would be in the full operations and ITS deployment scenario, as compared with a scenario that did not contain any operations and ITS deployments. This all-or-nothing approach was used to isolate the full costs and benefits of the operations and ITS deployments.

The FHWA's ITS Deployment Analysis System (IDAS) software was used in conjunction with the locally validated travel demand models for the three case study regions to predict the traffic conditions that would be likely in the two deployment scenarios—the No Operations and ITS Deployment Scenario and the Full Operations and ITS Deployment Scenario.

This analysis approach resulted in numerous regional performance measures being estimated for the two scenarios, such as the person-hours of travel, roadway speeds, the number of crashes, and the gallons of fuel used, among others. To identify the incremental impact resulting from the deployment of ITS, the performance measures from the Full Operations and ITS Deployment Scenario were subtracted from the identical performance measures for the No Operations and ITS Deployment Scenario. The difference between the performance measures between the two scenarios represented the incremental impact caused by ITS during the day or time period represented by the model data. The annual impact was determined by multiplying the daily incremental impact by the effective number of days per year.

For example, the Tucson case study used a single daily model in the analysis. To estimate the impact on any particular performance measure, such as the number of fatality crashes, the following approach was used:

Annual Benefit = (Number of Fatality Crashes Occurring in the No Operations and ITS Deployment Scenario – Number of Fatality Crashes Occurring in the Full Operations and ITS Deployment Scenario) * Effective Number of Days Per Year

For those models having multiple periods represented within a day, separate No Operations and ITS Deployment and Full Operations and ITS Deployment Scenarios were developed for each period. The performance measure for the No Operations and ITS Deployment and the Full Operations and ITS Deployment Scenarios were then compared within each period to identify the incremental impact. The incremental impacts from all the available time periods were then summed the daily impact.[1] This summed figure was then multiplied by the number of days per year to annualize the benefit. An example of this approach for annualizing the results for models with multiple time-of-day analysis is shown at the top of the next page.

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[1] The summing of the performance measures across all periods was performed for all cumulative impacts. Noncumulative performance measures, such as vehicle speeds, were not summed. Instead, these performance measures were calculated from the cumulative performance measures. For example, the estimate of daily speed was determined by summing the vehicle-miles traveled (VMT) for all periods and dividing by summed vehicle-hours traveled (VHT) for all periods.

$$\text{Annual Benefit} = \sum \begin{pmatrix} AMNO - AMFull \\ MDNO - MDFull \\ PMNO - PMFull \\ OPNO - OPFull \end{pmatrix} * \text{Number of Days per Year}$$

where

AMNo = Performance measure from the AM Peak Period: No Operations and ITS Deployment Scenario,

AMFull = Performance measure from the AM Peak Period: Full Operations and ITS Deployment Scenario,

MDNo = Performance measure from the Midday Period: No Operations and ITS Deployment Scenario,

MDFull = Performance measure from the Midday Period: Full Operations and ITS Deployment Scenario,

PMNo = Performance measure from the PM Peak Period: No Operations and ITS Deployment Scenario,

PMFull = Performance measure from the PM Peak Period: Full Operations and ITS Deployment Scenario,

OPNo = Performance measure from the Off-Peak Period: No Operations and ITS Deployment Scenario, and

OPFull = Performance measure from the Off-Peak Period: Full Operations and ITS Deployment Scenario.

The value of the annual benefit was then determined by applying the appropriate benefit values from the IDAS tool to the incremental change in the performance measures. The values from all the various performance measures were summed to determine the total annual benefit of all operations and ITS strategies included in the Full Operations and ITS Deployment Scenario. This benefit value was compared with the annual cost of the strategies to present the benefit–cost ratio for the included strategies.

Use of IDAS in Analyzing the Impacts of Full Operations and ITS Deployment

The IDAS software was developed by FHWA as a tool focused on analyzing the specific impacts of ITS. IDAS was also designed to serve as a repository of information on the impacts of various types of ITS deployments and of the costs associated with various types of ITS equipment. The default ITS impacts and costs used in the IDAS tool are based on the observed experiences of deploying agencies, as maintained in the U.S. DOT's ITS benefits and costs databases (www.benefitcost.its.dot.gov). By offering these capabilities, IDAS provides the ability to critically analyze and compare different ITS deployment strategies, prioritize the deployments, and compare the benefits of the ITS deployments with other improvements to better integrate ITS with traditional planning processes. Additional information regarding the structure of IDAS and its processes is presented in the *IDAS User's Manual*, which is distributed electronically with the IDAS software and is available on the IDAS web site at idas.camsys.com/documentation.htm.

The analysis of the impacts of full operations and ITS deployment used the default IDAS procedures, parameters, and impacts, except when noted. These parameters and impact values were held constant in the three case study regions to produce comparable results.

The following exceptions to the standard IDAS methodology were made in the analysis:

- *Estimation of Costs*: A separate cost estimation spreadsheet tool was developed outside the IDAS software to calculate the cost of the operations and ITS deployments. This spreadsheet tool applied the same methodology and used the identical equipment unit costs as the IDAS software. This external spreadsheet method was used to improve the ease of use for the analysts and better account for particular ITS equipment not currently represented in the IDAS software.
- *Estimation of the Impacts of Advanced Traveler Information Systems (ATIS)*: A blanket assumption of the overall effectiveness of all ATIS deployments was made, rather than make individual assumptions regarding the likely market penetration and effectiveness of each individual component. It was assumed that the various deployed ATIS components (pretrip and in-route systems) were successful in reaching 40% of travelers. Of those travelers receiving the information, 25% were able to save 6.3% of their travel time. This impact assumption was based on a comparison of the various IDAS impact assumption values for the individual ATIS components.
- *Comparison of Benefit–Cost Ratios*: An external spreadsheet tool was developed to compare the benefits and costs for the full deployment scenario. This separate spreadsheet was necessitated by the need to aggregate the results from multiple IDAS runs representing different periods (a.m., p.m., etc.). IDAS currently only has the ability to compare benefits and costs for a single period. This spreadsheet compiled the results from multiple time-period scenarios into combined daily and annual results.
- *Estimation of the Impacts of Weather and Work Zone Mitigation Strategies*: Weather and work zone mitigation strategies are not currently available as deployments within the IDAS software. Special analysis techniques were developed, using capabilities within the IDAS software, to analyze the impacts of these specific strategies. These techniques are described in a subsequent section.
- *Estimation of the Incident-Related Delay on Freeway Facilities*: The IDAS software contains a default calculation for estimating the incident-related delay for the freeway facilities, which is a function of four variables: roadway capacity, volume, number of incidents, and incident duration. Within the IDAS methodology, many different types of ITS and operations deployments may affect one or more of these variables. These impacts, as well as the impacts used for the other types of deployments, represent national averages of impacts observed following the deployment of these types of systems. Previous IDAS studies conducted by numerous agencies have served to vet these impacts, and they have generally been found to be rea-

sonable representations of the expected effect of the individual deployments. This study, however, includes combinations and intensities of deployment that exceed any that have been tested using this methodology, and it was the opinion of technical reviewers that the initial estimates of the cumulative impact to incident-related delay of all the deployments overstated the potential reduction. Subsequent sensitivity analysis revealed a large portion of the incident-related delay was related to the reduction in incident duration impact of the incident detection and management deployments. The default variable for this impact was reduced by 50%, and the analysis was rerun to produce the results. In the case of multitime period locations (Seattle and Cincinnati), this adjustment was rerun for a single representative time period, and the resulting reduction in the incident-related delay impact for the single period was used to factor the remaining periods.

D.3 MODEL NETWORKS AND ADJUSTMENTS

Network and travel demand data from the regional travel demand models formed the basis of the analysis. These models varied from region to region in their size and complexity. Additionally, some adjustments were necessary to modify the available travel demand model data to match the specific needs of the desired analysis. This section summarizes the models used in the three regions and describes the necessary modifications to generate the baseline data needed for the analysis.

Tucson

The model data available for the Tucson region represented daily travel conditions in the year 2025. This model was developed and maintained by the Pima Association of Governments (PAG). The Tucson model was the smallest of the models used in the analysis, representing a daily total of approximately 5.4 million person trips traveling between 870 possible origins and destinations. Three vehicle modes were represented in the model: auto, light truck, and heavy truck. Two public transit modes were represented; however, both represented bus travel. The transit modes were differentiated by the form of access to the transit stop: transit walk access and transit drive access.

No significant modifications were required to prepare the Tucson model data for use in the analysis. Minor reformatting of the data was performed to prepare the data for input into the IDAS software tool.

Cincinnati

The Cincinnati region model, obtained from the Ohio-Kentucky-Indiana Regional Council of Governments (OKI), was the most complex of the three regional models used in the analysis. The model had recently undergone a significant update, which resulted in the merging of the regional travel demand models representing the Cincinnati and Dayton, Ohio, regions. Models were specifically developed for this analysis representing travel demand for the year 2003. These models were developed to represent four separate periods: a.m. peak period (2.5 hours), midday peak period (6.5 hours), p.m. peak period (3.5 hours), and off-peak period (11.5 hours). The combined travel demand in these four periods represented approximately 9.3 million daily person trips traveling between 2,999 possible origins and destinations. Approximately 69% of this travel occurs in the Cincinnati region.

Adding to the complexity of the Cincinnati model was the disaggregation of travel into 11 possible modes, including five vehicle modes: single occupancy vehicle, high-occupancy vehicle (two persons), high-occupancy vehicle (three or more persons), single-unit truck, and multiple-unit truck. Six separate bus transit modes were also available, segmented by the type of bus service and access mode, including local bus walk access, local bus park and ride, local bus kiss and ride, express bus walk access, express bus park and ride, and express bus kiss and ride.

Several significant modifications were made to the existing Cincinnati models to prepare the data for use in this analysis. The first modification was the development of models representing travel in the year 2003. No specific existing models were available representing this year. Travel demand from models representing the year 2000 and 2010 were interpolated to develop travel demand trip tables for each of the analysis periods representing the year 2003. The model networks from the 2000 models were used since these models already contained roadway improvements that were expected to be completed by 2003.

A second modification was required to allow the analysis to focus only on the impacts in the Cincinnati region. The recent model update had merged the previous models from the Cincinnati and Dayton regions into a single model; however, the focus of this analysis was only on the Cincinnati region. A special data flag was added to the network link data to identify in which region each roadway was located. This enhancement allowed performance measures to be extracted from only those portions of the network located in the Cincinnati (OKI) region.

Other minor modifications were required to reformat the data for input into the IDAS software. Additional modifications were also required to perform a separate analysis of the impacts of weather and work zone mitigation strategies in the Cincinnati region. These specific modifications are discussed in a subsequent section.

Seattle

The Seattle regional models used in the analysis represented travel demand in the year 2003 for three separate periods: a.m. peak period, p.m. peak period, and the off-peak period. These models were based on the Puget Sound Regional Council (PSRC) travel demand models. These models represented a combined daily travel demand of approximately 10.8 million person trips traveling between 850 possible origins and destinations. Five separate travel modes were used in the analysis, including single occupancy vehicle, high-occupancy vehicle, truck, transit (bus and rail), and ferry.

Several modifications were made to the existing PSRC models to generate data suitable to the analysis of full operations and ITS deployment. The first modification was the development of specific models representing travel conditions in the year 2003. Travel demand data from existing year 2000 and 2005 models were interpolated to develop these interim year models.

A second modification to the Seattle model networks was required to allow the analysis of ramp metering strategies. On-ramp facilities are not represented in the current Seattle models. Instead, these interchanges are coded similar to surface street intersections and allow traffic to move directly from arterial roadways to freeway facilities. The IDAS software typically requires that ramp facilities be coded in the network to allow the analysis of ramp metering strategies. When ramp meters are deployed, additional impedance is added to the ramp facilities to simulate the impact of the ramp signal on traffic entering the freeway. Since the ramp facilities were not available in the Seattle model network, modifications were required to properly represent this impact. Turning movement restrictions, available for use in the IDAS software, were specially modified to represent the additional impedance caused by ramp metering strategies in the absence of ramp facilities.

A final modification to the Seattle models was required to properly represent automobile carrying ferries in the IDAS analysis. Some reformatting of the model data was necessary to properly account for the specific travel mode that is prevalent in the Puget Sound region.

D.4 ADDITIONAL ANALYSIS FOR ESTIMATING THE IMPACTS OF WEATHER AND WORK ZONES

Analysis Scenarios

Additional analysis was conducted in Cincinnati to identify the effects, benefits, and costs that could be expected with the addition of specialized operations and ITS strategies intended to counter the effects of inclement weather and help mitigate the negative impacts occurring because of road construction and maintenance.

Additional scenarios were needed to analyze these strategies because the baseline networks obtained from the travel demand model assume no inclement weather or road construction activity. The analysis scenarios that were developed differed by four separate variables: the presence of roadwork, weather conditions, deployment intensity, and time-of-day. These variables were defined as follows:

- *Presence of Roadwork*: Two separate roadwork scenarios were evaluated, including a network with a representative sample of construction activity and a network without road construction or reconstruction activity. The impact of roadwork activity was represented by reducing facility capacities through the construction zones, as described in a subsequent section.
- *Weather Conditions*: Three separate weather conditions were evaluated: clear, rain, and ice/snow. The network representing clear conditions was identical to the baseline network obtained from the travel demand model. The impacts of the rain and ice/snow conditions were represented by decreasing capacities throughout the network, as described in a subsequent section.
- *Deployment Intensity*: Several different deployment intensities were evaluated. These include a No Operations and ITS Deployment Scenario, which did not contain any ITS or operational improvements, and a Full Operations and ITS

Deployment Scenario, which contained the full complement of operations and ITS deployments. Note that for those scenarios that contained the negative impacts of inclement weather or construction activity conditions, the deployment scenario was enhanced by adding either weather or work zone mitigation strategies, or both, as appropriate to the conditions included in the scenario. These specific mitigation strategies were not included in the scenarios that did not contain either the inclement weather or construction activity. For example, the impacts of work zone mitigation strategies were analyzed only in those scenarios with roadwork conditions.

- *Time-of-Day*: Models representing four separate time periods were available for the Cincinnati region, including a.m. peak period, p.m. peak period, midday period, and off-peak.

An analysis approach was developed by creating a matrix of all the potential combinations of these variables and then discarding illogical combinations. For example, no scenarios analyzing conditions representing roadwork activity during ice/snow conditions were evaluated because little construction activity is anticipated in the winter months. To accommodate these variables in the analysis, 40 separate scenarios were developed and analyzed. Table D.1 presents these scenarios.

The following sections describe how the various impacts of weather and construction activity were simulated on the network to create these scenarios.

TABLE D.1 CINCINNATI ANALYSIS SCENARIOS

Weather	Construction Activity?	Scenarios with No Operations and ITS	Scenarios with Full Operations and ITS
Clear	No	a.m. peak Midday p.m. peak Off-peak	a.m. peak Midday p.m. Peak Off-peak
	Yes	a.m. peak Midday p.m. peak Off-peak	a.m. peak Midday p.m. peak Off-peak
Rain	No	a.m. peak Midday p.m. peak Off-peak	a.m. peak Midday p.m. peak Off-peak
	Yes	a.m. peak Midday p.m. peak Off-peak	a.m. peak Midday p.m. peak Off-peak
Ice/Snow	No	a.m. peak Midday p.m. peak Off-peak	a.m. peak Midday p.m. peak Off-peak

Simulation of Weather Impacts

Three different weather situations were considered in this analysis: clear, rain, and snow. Clear weather scenarios were represented using the baseline roadway network from the travel demand model. Scenarios representing rain and snow weather conditions were represented by reducing the capacity of network roadways to simulate the negative impact of the inclement weather. Weather impacts on capacity represented a weighted average of suggested capacity reductions from the *Highway Capacity Manual 2000* and the FHWA's Operations web site (www.ops.fhwa.dot.gov). The capacity reductions are shown in Table D.2.

TABLE D.2 CAPACITY REDUCTIONS USED TO REPRESENT INCLEMENT WEATHER CONDITIONS

Weather Condition	Freeway Reduction	Arterial Reduction
Clear	None	None
Rain	–6%	–6%
Ice/Snow	–10%	–12%

Simulation of Construction Activity Impacts

The negative impacts of construction activity were simulated on the model networks by first identifying a set of construction projects that would be representative of a typical construction season. These were identified by reviewing major regional construction projects from the previous 3 years and selecting a set of projects representative of a typical construction season. Eight projects were selected: four lane addition projects, two reconstruction projects, and two resurfacing projects. The construction schedules for these projects were also evaluated to estimate the typical number of days within a year in which construction activity was estimated to occur.

The construction projects were then coded into those scenarios meant to analyze work zone projects. Since the representative construction activities represent real projects, they were coded in the actual network locations they occurred. The negative impacts of the construction activities were simulated by reducing the baseline capacities for those roadway links identified as being within the construction zone. This reduction was conducted on an individual link-by-link basis, based on the initial number of roadway lanes, the number of lanes closed during construction, and the type of construction activity. The capacity reduction for each individual link included in the work zone was calculated by first subtracting out the number of lanes anticipated to be closed because of the construction activity. The capacities of the remaining lanes were then reduced based on the recommended capacity reduction factor from the highway capacity manual (based on the number of lanes in normal conditions and the type of construction activity). These capacity adjustments, for the lanes remaining open for the various projects, ranged from 75% of the original capacity for a two-lane facility undergoing resurfacing to 93% of the original capacity for a three- or more lane facility undergoing the addition of new lanes.

Additional Weather and Work Zone Mitigation Strategies

Additional weather and work zone mitigation strategies were deployed and analyzed in the appropriate Full Operations and ITS Deployment Scenarios containing the negative impacts of inclement weather and/or construction activity. These operations and ITS strategies are not currently included as available components for analysis within the IDAS tool. The software does have the capability, however, to deploy and analyze generic, user-defined components. For these generic deployments, the user is provided the opportunity to specify the impacts of the components. The components are then analyzed identically to all other existing deployments in the scenario, providing the opportunity to analyze the impacts of the user-defined components side-by-side with existing IDAS components to capture the full synergistic impacts of all components. This capability was used to simulate the weather and work zone improvements on the network.

The impacts used in the analysis to represent weather and work zone mitigation strategies were based on the observed impacts from these types of deployments, where available, or the impact of similar operations and ITS components already available within IDAS. The impacts associated with the various weather and work zone mitigation strategies are presented in Table D.3.

TABLE D.3 IMPACTS OF WEATHER AND WORK ZONE MITIGATION STRATEGIES

Strategy	Analysis Impact
Weather	
Weather advanced traveler information systems (ATIS)/ road weather information systems (RWIS)	ATIS information reaches 40% of regional travelers. Of those travelers receiving the information, 25% were able to save 6.3% of their travel time (based on existing IDAS ATIS methodology).
Work Zones	
Work zone ATIS	ATIS information reaches an additional 10% of travelers using the work zone corridors. Of those travelers receiving the information, 25% were able to save 6.3% of their travel time (based on existing IDAS ATIS methodology).
Work zone incident detection	15% reduction in incident duration in work zones. 15% reduction in fuel use rate and emissions rates in work zone (based on existing IDAS methodology and information from similar work zone deployment in Albuquerque, New Mexico).
Lane merging applications	5% restoration of facility capacity in work zone (based on information from the Midwest Smart Work Zone Deployment Initiative).
Alternative route management	10% increase in facility capacity for selected parallel arterial corridors serving as diversion routes (based on existing IDAS methodology for traffic signal coordination).
Alternative work hours	Reduction in the number of days (annually) with construction activity occurring in the peak hours. Offset by lesser increase in the number of days with construction occurring in the night-time period (based on information from the Midwest Smart Work Zone Deployment Initiative).

Estimating the Annual Impact of the Full ITS Deployment Scenario in Cincinnati

Each of the 40 individual scenarios was analyzed separately to estimate the likely traffic conditions that would occur for each given time-of-day period with similar weather, construction activity, and operations and ITS deployment intensity. The results of the individual scenarios were then annualized by applying a weight to each scenario representing how many days that scenario would be anticipated to occur in a typical year.

The applied weights were developed by reviewing historical weather patterns and construction schedules. Historical weather data from the National Weather Service revealed that rain would be expected to occur on 17% of days annually, and measurable snow/ice precipitation occurs on an average of 18 days per year. A similar review of the construction schedules of the representative projects included in the typical construction season indicated that construction activity would be expected to occur on 53% of the days annually. The analysis further assumed that 45% of the rain days would occur during the construction season.

The effective number of days in a year was assumed to be 250, representing the number of weekdays in a year, not including significant holidays. The historical rates of occurrence for the various weather and construction activities were then applied to identify weights (in number of days per year) for the No Operations and ITS Deployment Scenarios. The weights for the Full Operations and ITS Deployment Scenarios were weighted similarly, with the following exception. The weight representing number of days with construction activity in the peak periods was reduced to reflect the impact of alternative work scheduling strategies. The construction season for the off-peak scenarios was then extended to reflect the additional work shifted to the nighttime periods.

These identified weights were applied to each scenario and the resulting performance measures were summed for the No Operations and ITS Deployment and the Full Operations and ITS Deployment Scenario. The summed results were then compared to identify the annual incremental benefits of the Operations and ITS strategies. Table D.4 shows the annualization rates that were applied in the analysis for each possible scenario. Figure D.1 shows how the proportion of days included in the annualization changes between the No Operations and ITS Deployment and Full Operations and ITS Deployment Scenarios. For the peak periods (a.m., midday, and p.m.), the proportion of days with road construction is reduced between the No Operations and ITS Deployment and Full Operations and ITS Deployment Scenarios to represent the impacts of alternative work hours. These charts also show the impact of shifting some of these roadwork activities to the off-peak periods.

TABLE D.4 ANNUALIZATION WEIGHTS FOR CINCINNATI, OHIO

		AM		Midday		PM		Off-Peak	
Roadwork	**Weather**	**No Ops and ITS**	**Full Ops and ITS**	**No Ops and ITS**	**Full Ops and ITS**	**No Ops and ITS**	**Full Ops and ITS**	**No Ops and ITS**	**Full Ops and ITS**
No	Clear	49	66	49	66	49	66	49	32
No	Rain	21	24	21	24	21	24	21	18
No	Ice/Snow	46	46	46	46	46	46	46	46
Yes	Clear	113	96	113	96	113	96	113	130
Yes	Rain	21	18	21	18	21	18	21	24
Total		**250**	**250**	**250**	**250**	**250**	**250**	**250**	**250**

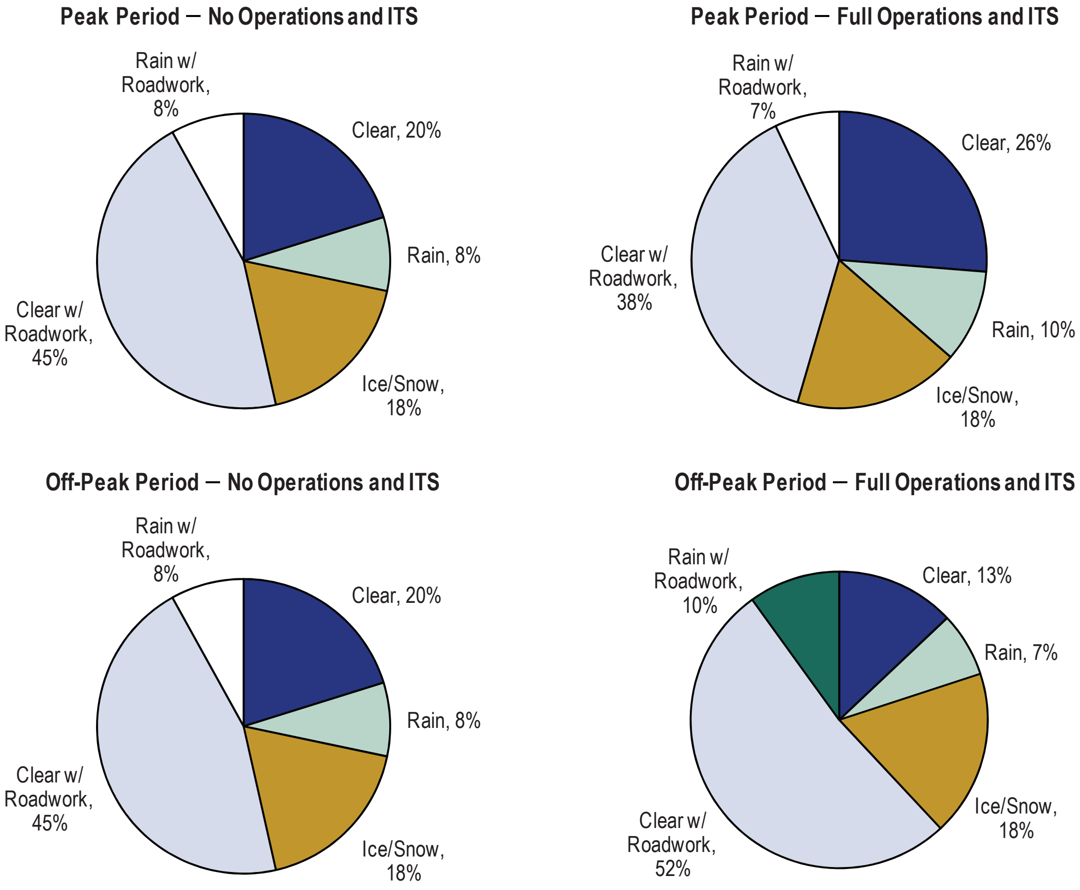

Figure D.1 *Proportion of days assumed for annualization.*

D.6 STUDY CAVEATS

As documented in this appendix, the analyses of the three case study regions were conducted using similar but not identical approaches and assumptions. Therefore, comparisons of major trends across the three regions are generally valid. Caution should be applied in any detailed crosscutting analysis of specific impacts, however, due to model and approach differences that may have skewed results. The differences in the approaches of the analyses may make it difficult to discern whether variations observed between the three regions are valid or are a product of the analysis methodology. Some of the significant variations in the models and approaches that have the potential to impact results are documented later in this appendix.

Tucson

The analysis of impacts in the Tucson region employed model data representing average daily travel in the year 2025. This region was the only one to use a future forecast of travel demand. The use of this future demand may result in the inflation of benefits, relative to other regions, since travel demand and related congestion is presumably greater than in the current year. The Tucson region was also the only region where a single daily forecast was used in the analysis. This unique characteristic may have the impact of decreased benefits relative to the other areas, because the daily traffic model does not capture the impacts of increased congestion during the peak hours. The Tucson model was also not adjusted to specifically analyze variations in weather conditions or construction activity, as was done in Cincinnati.

Cincinnati

The analysis of impacts in the Cincinnati region used model data representing travel conditions in 2003 for four separate periods—a.m. peak period, midday peak period, p.m. peak period, and off-peak period—with the sum of these periods equal to a single day. Further, additional models were constructed from these base models to represent traffic conditions during different combinations of weather conditions and road maintenance activity typifying a normal construction season. These additional models resulted in the analyses of ITS impacts during 20 unique traffic conditions, greatly adding sensitivity to the analysis compared with the other regions. Because the analysis produced increased benefit estimates for those alternatives representing inclement weather or construction activity, it is likely that the overall benefits estimated for Cincinnati are greater relative to the other areas. The analyses in Tucson and Seattle were not conducted with this sensitivity to weather conditions or construction activity and would not have captured these additional benefits.

Seattle

The Seattle regional models used in the analysis represented travel demand in the year 2003 for three separate periods: a.m. peak period, p.m. peak period, and the off-peak period. The results from the Seattle analysis are, therefore, sensitive to the variations in impacts caused by peak period congestion. The Seattle models were not adjusted, however, to specifically analyze variations in weather conditions or construction activity, as was performed in Cincinnati.

In addition to the model differences noted, other factors and parameters internal to the individual region's models may also affect the estimated impacts. Model characteristics such as the length of peak periods, volume-delay functions, and mode choice sensitivity may also promote differences in the analysis results.

Additional Caveats

Impacts of the operations and ITS deployments on incident-related delay were estimated in all three case study regions. The use of incident-related delay, nonrecurring congestion, or travel time reliability as a measure of system performance is an emerging practice. Yet there is often little consensus on the specific definitions of the performance measures used or the analysis methodologies applied in different studies. In this study, "incident-related delay" is estimated only for freeway facilities and represents the expected amount of delay occurring because of traffic incidents (crashes, stalls, and breakdowns). This performance measure is synonymous with the travel time reliability impact within the IDAS analysis methodology. Current incident data availability limits the application of this analysis methodology only to freeway facilities and does not currently allow for the estimation of incident-related delay for other surface roadways.

Other caveats, specific to the individual case study regions, are documented within the individual reports.

D.7 REFERENCE

1. *Highway Capacity Manual*. TRB, National Research Council, Washington, D.C., 2000.

E

DATA COLLECTION METHODS

Agencies can use five broad categories of traffic data sources to monitor travel time reliability:

1. Infrastructure-based detectors that can sense volume, occupancy, speed, and other data;
2. Automated vehicle identification (AVI) systems;
3. Automated vehicle location (AVL) systems;
4. Private-sector–based sources of traffic data; and
5. Event/incident data.

Public agencies typically own and operate the infrastructure-based detectors and the AVI systems used for tolls, whereas private, third-party sources often own and operate the AVL systems or collect data from other AVL sources. This section describes the use of each of these data sources for evaluating reliability.

E.1 INFRASTRUCTURE-BASED SOURCES

Infrastructure-based detectors, which include loop and radar detectors, are already a common component of traffic management systems in many regions. Some can measure vehicle speeds directly, while others use post-processing algorithms to estimate speeds based on counts and occupancy. The ones that can directly measure speeds are more valuable for measuring reliability.

While prevalent, these technologies have a drawback in that they only provide data at fixed locations along the roadway, meaning that they can only report spot speeds. Consequently, they cannot provide information on an individual vehicle's route or time of travel between two points. As a result, the data they transmit require some processing and extrapolation before travel times can be calculated. This also means that the accuracy of the travel time measures they produce is a function of how frequently detectors are spaced along the roadway. If existing deployments have detectors spaced at a frequency of ½ mi or less, they are suitable for inclusion in a reliability monitoring system. If detectors are placed less frequently on key routes, agencies may want to consider either installing more detectors or supplementing the existing detection with AVI sensors.

The following types of technologies are considered infrastructure-based sources:

- *Loop Detectors*: Loop detectors are located in the pavement on many roadway facilities. They have historically been the most common traffic-monitoring tool because of their relatively low installation cost and high performance. Coverage, however, varies greatly among cities and states. In many urban locations, they are common on freeway facilities. Many arterials also use loop detectors to control actuated and adaptive traffic signals. However, it should be noted that loop detectors used in traffic-responsive signal systems are usually not well adapted to providing the data required to support reliability monitoring. In some cases it is possible for agencies to modify the existing signal system sensors to collect additional data and transmit them to a centralized location to support reliability monitoring. Loop detectors typically measure traffic volumes and occupancies and send data to a centralized location every 20 to 60 seconds. From these data, spot speeds can be calculated with a reasonable accuracy and used to extrapolate travel times. Loop detectors in a dual configuration (two closely spaced loops) can directly report speed values. Two drawbacks with loop detectors are their intrusive installation and their significant maintenance requirements. For this reason, it is typically recommended that agencies only use loop detectors for reliability monitoring in locations where they already exist.
- *Wireless Magnetometer Detectors*: Like loop detectors, wireless magnetometer detectors are located in the road but can be installed simply by drilling a hole into the pavement, eliminating the need for cutting pavement during installation and reducing maintenance requirements. These sensors use radio signals to communicate with access points located on the roadside, usually on poles or the cabinet, preventing the need to hardwire a detector to a controller cabinet. Like loop detectors, they report volume and occupancy data with a granularity that depends on the sensor's setting. Sensors in a dual configuration can also directly report speed values. The data accuracy of wireless magnetometer detectors is similar to that of loops. Where agencies would like to install additional in-road infrastructure detectors, wireless magnetometer sensors are a good alternative to loop detectors. Recent developments have also adapted some wireless magnetometer detectors to re-identify vehicles at a second detector, giving them AVI capabilities.
- *Video Image Processors*: Many agencies have begun installing video image processors, on both arterial and freeway facilities, as an alternative for loop detection. Video image processing can retrieve volume, occupancy, and speed data from cameras on the roadway. This technology usually requires users to manually set up

detection zones on a computer that are in the field of view of each camera, meaning that it is important that the cameras not be moved and the detection zones be set up correctly. Some specialized systems can also re-identify vehicles detected at two separate cameras, giving them AVI capabilities. This technology is a viable method for travel time reliability monitoring where agencies already have cameras installed.

- *Radar Detectors*: To overcome the intrusive installation and maintenance of loop detectors, many agencies have deployed microwave radar detectors, which are placed overhead or roadside and measure volume and speed data. One drawback to radar detectors is that they can lose their speed calibrations. Additionally, they can be sensitive to bad weather conditions such as snow, fog, or temperature change. Radar detectors are a viable option for agencies that want to increase the frequency of data collection infrastructure along a roadway without installing more loop detectors.
- *Other Infrastructure-Based Sources*: A number of additional overhead vehicle detection technologies have capabilities similar to microwave radar detectors: passive infrared sensors, ultrasonic sensors, and passive acoustic array sensors. These technologies can be considered on a site-specific basis or used for travel time reliability monitoring where they have already been deployed.

E.2 AUTOMATED VEHICLE IDENTIFICATION SOURCES

Automated vehicle identification (AVI) data collection sources detect a passing vehicle at one sensor and then re-identify the vehicle at a second sensor, allowing the vehicle's travel time between two points to be directly computed. The drawback of AVI technologies is that while they provide the travel time between two points, they cannot inform on the route taken by individual vehicles or whether the trip included any stops. Because there are often multiple ways to travel between two points, especially in urban areas, some processing and filtering is required to ensure that reliability computations are based on representative travel times for a given route. Inaccuracies can also be reduced by deploying sensor readers at frequent intervals, to reduce the likelihood that a vehicle took a different route than the one assumed in the computation. The following technologies are sources for AVI travel time data.

- *Bluetooth*: Bluetooth receiver technology has only recently been applied to traffic data collection, but it appears to be promising for measuring travel times. The technology will be especially useful for arterial data collection given that the more traditional methods are not effective on arterials. Bluetooth detectors record the public media access control (MAC) address of a driver's mobile phone or other consumer electronic device as the vehicle passes a point. This recorded ID number (or a truncated version of it, to reduce privacy concerns) can then be matched as the vehicle passes subsequent detectors, allowing travel times between points to be calculated.

This technology is advantageous in that it is accurate, low-cost, and portable. A drawback, however, is that currently only a small percentage of drivers have Bluetooth-enabled devices in their vehicles; recent (2010) study estimates range from 5% in the Washington, D.C., metropolitan area to 1% outside of Indianapolis. It can be assumed that these percentages will grow, as commercial Bluetooth applications, particularly smart phones, become more prevalent, making Bluetooth an important data collection alternative for future projects. A few issues with Bluetooth measurements need to be accounted for in the data filtration process. First, Bluetooth readers frequently record the same wireless network ID more than once as a vehicle passes, especially when vehicles are traveling slowly. These duplicate addresses need to be removed to avoid counting a vehicle's travel time more than once. Second, Bluetooth readers have a wide detection range that could collect travel times that do not reflect actual conditions. For example, a Bluetooth sensor station on a freeway might detect a vehicle that is in a queue on an entrance ramp and as a result a longer than accurate travel time would be reported. These nonrepresentative travel times would have to be filtered out during data processing. Additionally, on arterial streets, Bluetooth readers report travel times from nonvehicular modes like walking or cycling, so these times would have to be removed in the data cleaning process.

- *License Plate Readers*: License plate readers (LPR) employ cameras that capture a digital image of a vehicle's license plate and use optical character recognition (OCR) to read the plate number. While primarily used for toll enforcement, LPR can also be used to calculate travel times for vehicles that pass by two or more cameras. The advantage of LPR is that it can collect travel time samples from vehicles without requiring the presence of any specific device within the vehicle. This method, however, is not well suited for data collection on high-speed freeways. Additionally, plate matching is not always accurate, especially during adverse weather conditions. The equipment needed is also costly, and there are privacy concerns that come with tracking a vehicle by its license plate number. The percentage of successful license plate matches is about 5% to 20% in a given period. Due to LPR's accuracy issues and high cost, it is recommended that only those locations that have already installed LPR infrastructure use it as a primary method of data collection for reliability monitoring.
- *Radio-Frequency Identification*: Radio-Frequency Identification (RFID) technology is employed in electronic toll collection (ETC) and can be used to re-identify vehicles for travel time purposes. RFID is embedded in toll tags such as EZPass on the East Coast and FasTrak in the San Francisco Bay Area. More than 20 states currently have locations that use RFID toll tags. The iFlorida toll tag travel time project found that toll tag penetration is high in urban areas with toll roads, but much lower in other areas. This means that this data collection option is best suited for urban areas with a high toll tag saturation rate. The study found comparable rates of saturation between urban freeways and urban arterials; however, the percentage of vehicles that could be re-identified at a second sensor was lower for arterials because more vehicles enter and exit the facility between sensor stations.

As a result, in Orlando, toll tag readers usually only generated between 10 and 20 travel time estimates per hour. Agencies should thoroughly evaluate their regional saturation rate of RFID toll tags to determine whether this technology can supply the number of travel time samples needed to robustly estimate reliability measures over time. Aside from sample size concerns, privacy issues are raised, because RFID transmits data that are identifiable to an individual vehicle. Therefore, if RFID is used to collect travel times, the system will need to encrypt data to remove personal information. The iFlorida deployment does this by sending the DOT database an encrypted key that represents the toll tag number, rather than the actual toll tag number itself.

- *Vehicle Signature Matching*: Vehicle signature matching refers to methods that match the unique magnetic signature of a vehicle as it passes over a loop to the same signature from an upstream loop. Single loop, double loop, and wireless magnetometer detectors all have this capability. While loops are not capable of matching every vehicle, research and testing of this method has shown that it can match enough vehicles to provide accurate travel time distributions for both freeways and arterials.

One advantage of this method is that it can use preexisting detectors in new ways that improve travel time data accuracy. For arterials, it is advantageous over traditional detector data, since it estimates travel times without the need for signal phase information. It also offers an additional benefit over other AVI technologies: it avoids potential privacy concerns through anonymity. This technology has only seen limited use in practice thus far, with projects in a few locations in California, but it appears promising for measuring travel times on both freeways and arterials.

E.3 AUTOMATED VEHICLE LOCATION SOURCES

Automated Vehicle Location (AVL) refers to technologies that track a vehicle along its entire path of travel. These methods provide the most accurate and direct measurements of travel times, but have not yet seen deployment sufficient to provide reliable data on a regional scale. This will change as more vehicles become equipped with AVL technologies and agencies become more accustomed to using them for real-time data collection.

- *Global Positioning System (GPS)*: Any vehicle equipped with a GPS-based receiver can be tracked along its path of travel to calculate route-based travel times and other traffic data. GPS technology is well suited for accurate travel time calculations because it can pinpoint a car’s location within a few meters and its speed within 3 mph. GPS has traditionally been used to calculate travel times through test probe vehicles equipped with GPS receivers. The value of these data is limited because of the small number of test probe vehicles typically deployed, and they do not provide real-time data on a permanent basis. However, even in a more advanced system that monitors all GPS-equipped vehicles in real time, the low market penetration rate of GPS technology will be a constraint on the ability to accurately represent travel time variations. However, it can be reasonably assumed that more vehicles and devices will have GPS capabilities in the future. GPS is also used by many transit agencies to monitor bus locations and schedule adherence in real time. As such, another alternative for agencies looking to monitor reliability is to use equipped buses as travel time probes. By identifying and factoring out bus-specific activities, such as dwell times and different acceleration rates, arterial travel times can be estimated from bus AVL data.

- *Connected Vehicle Initiative*: The Connected Vehicle Initiative, sponsored by the U.S. DOT, is focused on leveraging wireless technology to allow vehicles and roadway facilities to communicate with one another, with the aim of improving safety, monitoring conditions, and providing traveler information. The majority of connected vehicle research will be completed by 2013, so it is impossible to know the full scope of the contributions that connected vehicles will make to reliability monitoring efforts. At this point, however, it seems that connected vehicle technologies could provide a rich source of travel time information, since the vehicle to infrastructure (V2I) communication channels implemented through the program could be used to send collected vehicle-specific location data to a central data server for travel time processing.
- *Urban Congestion Report*: The Urban Congestion Report, sponsored by the FHWA Office of Operations, is produced on a quarterly basis and characterizes congestion and reliability trends at the national and city level. The reports are designed to provide timely congestion and reliability information to state and local agencies; demonstrate the use of archived traffic operations data for performance monitoring; and promote state and local performance monitoring to support transportation decision making. The reports are based on archived traffic operations data gathered for 23 urban areas. However, the FHWA is examining the use of private sector travel time and speed data, as evidenced in their July 2011 report, *Private Sector Data for Performance Management: Final Report*.
- *Cellular Telephone*: Cellular telephone networks track cell phones to hand them off to different base stations as they travel, and travel times can be calculated through this information. The precision of location data increases with the number of cellular towers that a phone is in range of. In urban areas, location accuracy can be within 100 feet, which in some cases is too large to assign vehicles to a specific link, especially in dense urban networks. In rural areas, location accuracy can be wrong by more than a mile, which would negate the value of travel times estimated in this manner. To obtain cellular travel times for reliability monitoring, agencies must either collaborate with cell phone companies or buy data from a third-party provider. This technology is currently being used as part of the Transportation Technology Innovation and Demonstration (TTID) Program. The contractor, Traffic.com-NAVTEQ, combines information from multiple probe technologies including a proprietary sensor network, commercial and consumer GPS and cellular phone probes, and incident and event data. The data are then fused to provide real-time travel time estimates and incident information.

E.4 PRIVATE-SECTOR–BASED SOURCES

In addition to the public sector sources described previously, private sources of data can be used to support reliability analysis.

SHRP 2 Project L02 conducted a series of focus group interviews on data collection practices and business processes related to measuring, monitoring, and recording travel time reliability information. The interview results established that many agencies are interested in obtaining data from private sources, in order to save time and money on data collection and processing. While these private sources can provide data for facilities that are otherwise unmonitored (such as arterials), the lack of transparency on their proprietary methods of data collection presents challenges for agencies seeking to monitor reliability.

These companies provide data to public agencies as a sideline to their core business, providing travel time and other data to the traveler information market. For public agencies, most commercial vendors provide a speed range (e.g., 30 to 40 mph) for stretches of roadway defined by Traffic Message Channel (TMC) IDs during a fixed period (e.g., 5- or 15-min or hour-long increments). (TMCs represent a consistent location referencing method agreed upon by the traveler information industry.) These data are, by their very nature, opaque to agencies. For example, it is not clear where on that stretch of roadway the speeds were observed or when during the period they were observed. More importantly, little information is given on the methods used to calculate the speeds. For example, the speeds may have been calculated from multiple GPS probe readings on the roadway and thus may be highly accurate, or they may have been interpolated entirely from historical data because no real-time samples were collected during the period.

Data Sources

These private source firms collect data from a variety of ITS sources, including GPS probes, road sensors (both publically and privately owned), toll tags, and smart phones. Many of these firms also collect incident and event data.

The simplest data these firms collect are fixed roadway sensors. These are largely the result of a series of public-private partnerships, stretching back to the mid-1990s, in which firms were allowed to install and maintain fixed detectors on public roadways, usually in exchange for an exclusive concession to sell the traffic data to another market, such as the local media market. Typically, these data are available already to the public agency, as part of the concession. In some cases, the agency might procure these data or additional rights to data they already receive (as part of a new travel time reliability system, for example). Often the private firms also receive the publically available agency sensor data from traffic management agencies.

Increasingly, private vendors are also collecting probe data. Probe data have historically been the purview of freight companies, who have the necessary cost incentives to equip their vehicles with GPS. For example, freight companies can rent or purchase tracking devices to place on vehicles and then pay a flat communication fee to receive web access and real-time alerts on vehicle locations. Thus, the first data sources for private providers were primarily freight carriers. However, in a world of cheaper GPS and ubiquitous smart phones, this is rapidly changing. Currently, an estimated 35% of drivers have smart phones, many of whom use the device's GPS capabilities in-vehicle for navigation assistance. Firms are increasingly acquiring data directly from consumers as part of the growing personal navigation market. Consequently, the size and diversity of the probe data sets are exploding.

Data Transparency

While some providers may supply metadata on the data quality (e.g., a ranking scale), the methods for the quality assessment are also opaque. For the most part, these limitations are inherent to the business model of the data provider. Private source data providers have built their competitive advantage on their network of data sources and data fusion methodologies. Because of this, they are unlikely to reveal the underlying sources and methodologies to transportation agencies. This fact must be considered by agencies interested in using private source data to produce or supplement reliability information.

The ability to accurately report on travel time reliability has improved considerably over the last few years as the number and coverage of data sources including private probe data increase. Several technical and institutional challenges are associated with using and integrating probe data. Technical challenges include validating the resulting speed measurements with actual speeds, ensuring that sample sizes are adequate, and geolocating data from the standard traffic message channel (TMC) to coincide with state linear referencing systems. Institutional challenges include licensing data, privacy concerns, ownership, rights, usage, and resale of data. The report *Private Sector Data for Performance Management*, prepared for FHWA in July 2011, describes the challenges and examines issues surrounding blended traffic data. The report also discusses integration of private sector travel time data with public agency traffic volume data.

Agencies may want to test the data quality issue by

- Building travel time distributions out of the speed-binned data, to see if these simplified distributions were adequate to its needs; and
- Purchasing a data sample from a firm and independently testing its quality.

E.5 EVENT AND INCIDENT DATA COLLECTION

Traffic data are not the only data that will inform transportation analysts on travel time reliability; other event and incident data also provide reliability information. Many agencies in the United States routinely track incidents and incident duration, weather, work zone lane closures, and special events. In most cases, staff working in a traffic management center (TMC) use tracking software to monitor these incidents and events. While it is possible to track these events manually in a spreadsheet, it is a time-consuming task. Most TMCs track incidents automatically, using the operator software. Additionally, a number of TMCs also log work zone lane closures by location and duration of the closure and special events in their traffic management plans. The most sophisticated TMCs track the duration and timeline of incidents as they are happening by saving operator actions time stamps. These time stamps can be used to determine the time the lanes were closed for an incident, the agency response time, and what time the lanes were cleared. This information, along with the traffic data, provides a complete history of an incident's impacts.

E.6 DATA INTEGRATION

Accessible and quality data are the foundation of performance management and technical analysis that support investment decisions. Effective decision making in each element of the performance management framework requires that data be collected, cleaned, accessed, analyzed, and displayed. Therefore, the national and state focus on performance measurement has resulted in several states evaluating and improving their data programs and systems. A variety of methods and tools are being used across the country to assess, evaluate, and prioritize data programs. At the same time, the information industry benefits from continued rapid changes in technology and infrastructure for data sharing as the breadth of technologies for data management and dissemination continues to increase and the complexity and cost of deploying these tools continues to fall.

F

U.S. DOT GUIDANCE ON PERFORMANCE MEASURES

F.1 CALCULATION PROCEDURES FOR KEY INTEGRATED CORRIDOR PERFORMANCE MEASURES FROM SIMULATION OUTPUTS

A core element of the integrated corridor management (ICM) initiative is the identification and refinement of a set of key performance measures. These measures represent both the bottom line for ICM strategy evaluation and define what “good” looks like among key corridor stakeholders. To date, the emphasis on performance-driven corridor management among the participating pioneer sites has been on measures derived from observed data. In the Analysis, Modeling, and Simulation (AMS) phase of the effort, however, attention has turned to producing comparable measures derived from simulation outputs. This document provides a detailed process by which a set of key national measures of corridor performance can be calculated. It is the intent of the ICM program, and this document, that these processes will be implemented consistently in the three participating AMS sites applying the ICM AMS methodology.

This document provides a detailed description of how measures of delay, travel time reliability, and throughput are calculated from simulation outputs. A brief discussion of travel time variance is also provided, given that travel time variance measures are used in ICM-related, benefit–cost calculations. The algorithmic approaches defined here are software independent; that is, this process can be implemented with outputs from any of the time-variant simulation tools utilized in the three participating ICM AMS sites. This appendix begins with a discussion of the calculation of travel time, which informs both a calculation of delay and travel time reliability. A discussion of how corridor throughput is defined and measured follows. The appendix concludes with a discussion of how these measures are used to make comparisons between system performance in the pre-ICM case and in one or more distinct post-ICM cases.

Travel Time

Our basic unit of observation in calculating ICM-related performance measures is a trip i made between an origin o, finishing at a destination d, starting at a particular time τ using mode m.

We record travel time from a single run of the simulation under operational conditions k for this unit of observation as $t_i^k = t_{o,d,\tau,m}^k$.[1] *Operational conditions* here refer to a specific set of simulation settings reflecting a specific travel demand pattern and collection of incidents derived from a cluster analysis of observed traffic count data and incident data. An example of an operational condition would be an a.m. peak analysis with 5% higher than normal demand and a major arterial incident.

First, for this particular run(s) representing a specific operational condition, we calculate an average travel time for trips between the same O-D pair that begin in a particular time window. Let τ represent this interval (e.g., an interval between 6:30 a.m. and 6:45 a.m.) and $\mathrm{I}_{o,d,\tau,m}^k$ the set of $n_{o,d,\tau,m}^k$ trips from o to d starting in interval τ under operational condition k using mode m. Note that $\mathrm{I}_{o,d,\tau,m}^k$ is a collection of trips and $n_{o,d,\tau,m}^k$ the scalar value indicating the number of trips contained in $\mathrm{I}_{o,d,\tau,m}^k$.

The classification of travel mode may be determined independently at each site, but the breakdown should capture the combination of all modes used in making the trip. For example, one may choose to classify a non-HOV auto trip as a distinct mode from non-HOV auto/HOV/walk trip to track the performance of travelers using park-and-ride facilities. However, any classification of modes must be mutually exclusive and collectively exhaustive; that is, $\bigcup_m \mathbf{I}_{o,d,\tau,m}^k = \mathbf{I}_{o,d,\tau}^k$ and $\sum_m n_{o,d,\tau,m}^k = n_{o,d,\tau}^k$.

The average travel time of trips with origin and destination by mode starting in this time interval is:

$$T_{o,d,\tau,m}^k = \frac{\sum_{i \in \mathbf{I}_{o,d,\tau}^k} t_i^k}{n_{o,d,\tau,m}^k} \tag{F.1}$$

The calculation of Equation F.1 must also include some estimated travel time for trips that cannot reach their destinations by the end of the simulation period. Later in this document, a method will be discussed for estimating travel times for these trips still under way when the simulation ends.

Next, we calculate the average travel time for this same set of trips across all operational conditions. Let k be a specific operational condition and the set of all conditions K. Note that each condition has a probability of occurrence p_k and $\sum_k p_k = 1$.

Equation F.2 finds the average travel time by mode for all trips from o to d starting in interval τ over all conditions $k \in K$:

$$T_{o,d,\tau,m} = \sum_{k \in K} T_{o,d,\tau,m}^k p_k \tag{F.2}$$

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[1] In the case where multiple random seeds are varied but the operational conditions are identical, this travel time represents an average for a single trip in across the multiple runs. Also, note that this discussion of measures assumes that we are calculating measures for a single case (e.g., pre-ICM); later we will address comparisons between cases.

The average number of trips by mode from o to d starting in interval τ over all conditions $k \in K$:

$$n_{o,d,\tau,m} = \sum_{k \in K} n^k_{o,d,\tau,m} p_k \tag{F.2a}$$

Combining across modes, the average travel time of trips from o to d starting in interval τ under operational condition k:

$$T^k_{o,d,\tau} = \frac{\sum_m T^k_{o,d,\tau,m} n^k_{o,d,\tau,m}}{n^k_{o,d,\tau}} \tag{F.3}$$

The average travel time for all trips from o to d starting in interval τ over all conditions $k \in K$:

$$T_{o,d,\tau} = \sum_{k \in K} T^k_{o,d,\tau} p_k \tag{F.4}$$

The average number of trips from o to d starting in interval τ over all conditions $k \in K$:

$$n_{o,d,\tau} = \sum_{k \in K} n^k_{o,d,\tau} p_k \tag{F.4a}$$

Equation F.5 defines the trip-weighted average travel time of the system across all o,d,τ:

$$T = \frac{\sum_{\forall o,d,\tau} T_{o,d,\tau} n_{o,d,\tau}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \tag{F.5}$$

Delay

Delay can be broadly defined as travel time in excess of some *subjective minimum* travel time threshold. Often, discussions of delay that focus solely on roadway-only travel focus on either travel time at posted speeds or 85th percentile speeds. Delay for ICM must be defined differently, since ICM explicitly includes multimodal corridor performance. Instead, we directly identify delay at the o,d,τ level by deriving a zero-delay threshold by mode $T^0_{o,d,\tau,m}$.

This can be derived from travel time outputs over all operational conditions:

$$T^0_{o,d,\tau,m} = \min_{k \in K} \left\{ T^k_{o,d,\tau,m} \right\} \tag{F.6}$$

In some cases, the cluster analysis will group low-demand, non-incident conditions into a large, high-probability operational condition. In this case, it is possible that a notionally low demand pattern will still produce significant congestion in the corridor, particularly in a peak-period analysis.

For this reason, the minimum threshold may also be calculated as the travel time derived in the pre-ICM case under a substantially reduced demand pattern with no incidents or weather impacts. The reduced demand pattern should generate a large enough number of trips to generate travel time statistics by mode for every set of trips from o to d starting in interval τ (i.e., $n^0_{o,d,\tau,m} > 0 \forall o,d,\tau,m$). At the same time, the reduced demand should generate no volume-related congestion in the network.

Alternatively, $T^0_{o,d,\tau,m}$ may be estimated directly from model inputs. For consistency, however, the travel time associated with these thresholds should include expected transfer time between modes and unsaturated signal delay, as in the case where a low-demand pattern is used to drive a zero-delay model run.

Once zero-delay thresholds $T^0_{o,d,\tau,m}$ are identified, average trip delay can be calculated by mode for each o,d,τ,m:

$$D_{o,d,\tau,m} = \max\left[T_{o,d,\tau,m} - T^0_{o,d,\tau,m}, 0\right] \tag{F.7}$$

Combining across modes, the average delay for trips from o to d starting in interval τ:

$$D_{o,d,\tau} = \frac{\sum_m D_{o,d,\tau,m}}{n_{o,d,\tau}} \tag{F.8}$$

Systemwide average trip delay (Equation F.9):

$$D = \frac{\sum_{\forall o,d,\tau} D_{o,d,\tau} n_{o,d,\tau}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \tag{F.9}$$

Aggregating this average delay over all trips produces total system delay (Equation F.10):

$$\hat{D} = \sum_{\forall o,d,\tau} D_{o,d,\tau} n_{o,d,\tau} \tag{F.10}$$

Travel Time Reliability

Corridor reliability measures are inherently measures of outlier travel times experienced by a traveler making the same (or similar) trip over many days and operational conditions. This is convenient, given that we have already defined and organized travel time measures from the simulation with respect to trips from o to d starting in interval τ over all conditions $k \in K$. Just as in the case of the subjective notion of delay as travel time in excess of some minimum threshold, the notion of what reliable travel depends on a *relative maximum* acceptable travel time threshold. For the ICM AMS effort, as in many studies with a travel reliability measure, a threshold based on the 95th percentile travel time is selected. Note that this percentile is calculated considering travel times for similar trips (i.e., o,d,τ) with respect to travel time variation induced by changes in operational conditions $k \in K$.

To identify the 95th percentile travel time, we first generate an ordered list of travel times by o,d,τ:

$$\mathbf{T}_{o,d,\tau} = \left[T^{1}_{o,d,\tau}, T^{2}_{o,d,\tau}, \ldots, T^{J}_{o,d,\tau} \right], \text{ where } T^{j}_{o,d,\tau} \le T^{j+1}_{o,d,\tau} \text{ for all } j = 1 \ldots J \qquad \text{(F.11)}$$

The 95th percentile travel time from this list is identified using the probabilities associated with each operational condition.

$$T^{[95]}_{o,d,\tau} = T^{j}_{o,d,\tau} \text{ where } \sum_{k-1}^{j} p_k = 0.95. \qquad \text{(F.11a)}$$

Note the array of travel times $\mathbf{T}_{o,d,\tau}$ represents levels on a linear step function. This implies that, if 17.4 min is the travel time associated with an operational condition occupying the 92nd through 98th travel time percentile, we simply use the 17.4-min travel time as the 95th percentile value. Also, note that the specific operational conditions under which the 95th percentile travel time is found will vary among o,d,τ. For example, a major freeway incident creates congestion and high travel times for trips that originate upstream of the incident location, but creates free-flowing and uncongested conditions for trips that originate downstream of the incident location.

Equation F.12 defines planning time index, the ratio of the 95th percentile travel time to the zero-delay travel time for trips from o to d starting in interval τ over all conditions $k \in K$:

$$\rho_{o,d,\tau} = \frac{T^{[95]}_{o,d,\tau}}{T^{0}_{o,d,\tau}} \qquad \text{(F.12)}$$

Average systemwide planning time index considers all o,d,τ weighted average by trip volume:

$$\rho = \frac{\sum_{\forall o,d,\tau} \rho_{o,d,\tau} n_{o,d,\tau}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \qquad \text{(F.13)}$$

Variance in Travel Time

Variance in travel time can be calculated in a variety of ways. The key here is that some care must be taken to isolate the specific variation of interest.

For example, variance in travel time among members of the same time interval in a single run is the variance of $t_{o,d,\tau}$ with respect to $\tau' \in \tau$:

$$V^{k}_{o,d,\tau} = \frac{\sum_{\tau' \in \tau} \left(t^{k}_{o,d,\tau'} - T^{k}_{o,d,\tau} \right)^2}{n^{k}_{o,d,\tau} - 1} \qquad \text{(F.14)}$$

If we seek to identify the variance in conditions that are reflective of a traveler making the same trip at roughly the same time on a regular basis, however, the unit of observation is the o,d,τ trip-making window with respect to $k \in K$. In this case, the calculation of variance also includes the consideration of the probabilities of each operational condition.[2]

$$V_{o,d,\tau} = \sum_{k \in K} \left(T^k_{o,d,\tau} - T_{o,d,\tau} \right)^2 p_k \tag{F.14a}$$

The average variance among all o,d,τ is a weighted average of the variances:

$$V = \frac{\sum_{\forall o,d,\tau} V_{o,d,\tau} n_{o,d,\tau}}{\sum_{\forall o,d,\tau} n_{o,d,\tau}} \tag{F.14b}$$

Throughput

The role of a throughput measure in ICM is to capture the primary product of the transportation system: travel. Particularly in peak periods, the capability of the transportation infrastructure to operate at a high level of efficiency is reduced. One of the goals of ICM is to manage the various networks (freeway, arterial, transit) cooperatively to deliver a higher level of realized system capacity in peak periods. While throughput (e.g., vehicles per lane per hour) is a well-established traffic engineering point measure (that is, in a single location), there is no consensus on a systemwide analog measure. In the ICM AMS effort, the term *corridor throughput* is used to describe a class of measures used to characterize the capability of the integrated transportation system to efficiently and effectively transport travelers. We do not consider freight throughput in these calculations, although this could be revisited later.

To support throughput measures, additional trip data need to be generated as simulation outputs. For each trip i made between an origin o, finishing at a destination d, starting at a particular time τ' we obtain from the simulation the travel time $t^k_{o,d,\tau'}$ and a distance traveled $s^k_{o,d,\tau'}$. In some cases, trip-level outputs from the simulation are only available at a vehicle level, so some trips may have multiple passengers associated with that trip (e.g., in the case of carpool travel). Let $x^k_{o,d,\tau'}$ represent the number of travelers associated with a particular trip record.

Passenger-miles traveled (PMT) are accumulated using a process similar to travel time. First, we convert individual trip PMT into an average PMT for trips from origin o to destination d with a trip start in time interval τ.

$$X^k_{o,d,\tau} = \frac{\sum_{i \in \mathrm{I}^k_{o,d,\tau}} s^k_i x^k_i}{n^k_{o,d,\tau}} \tag{F.15}$$

For trips that cannot be completed before the end of the simulation, see the following section for the estimation of total trip distance.

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[2] We make a simplifying assumption that the unbiased variance is well approximated by the biased variance in this case; that is, we do not estimate the sum of the individual weights squared.

Equation F.16 finds the average PMT for all trips from o to d starting in interval τ over all operational conditions $k \in K$:

$$X_{o,d,\tau} = \sum_{k \in K} X^{k}_{o,d,\tau} p_k \tag{F.16}$$

Equation F.17 defines the aggregate PMT across all o,d,τ:

$$X = \sum_{\forall o,d,\tau} X_{o,d,\tau} n_{o,d,\tau} \tag{F.17}$$

Passenger-miles delivered (PMD) and passenger-trips delivered (PTD) are measures that introduce notions of travel quality into throughput. Simple PMT measures often cannot differentiate between a well-managed system and a poorly managed system because passenger-trip distances are counted equally, regardless of trip duration. In other words, a 5-mi trip completed in 15 min counts equally with the same 5-mi trip completed in 2 h. Here, we restrict the accounting of passenger-miles traveled (or passenger-trips delivered) to trips that successfully complete their trips before the end of the simulation (or some other logical time-point). Let $\dot{\mathrm{I}}^{k}_{o,d,\tau}$ be the set of trips from from o to d starting in interval τ under operational condition k that complete their trip before the simulation ends (or some other logical time-cutoff).

Equation F.18 shows passenger-trips delivered (PTD) calculated at the o,d,τ level.

$$Y^{k}_{o,d,\tau} = \frac{\sum_{i \in \dot{\mathrm{I}}^{k}_{o,d,\tau}} x^{k}_{i}}{n^{k}_{o,d,\tau}} \tag{F.18}$$

Equation F.19 finds the average PTD for all trips from o to d starting in interval τ over all operational conditions $k \in K$:

$$Y_{o,d,\tau} = \sum_{k \in K} Y^{k}_{o,d,\tau} p_k \tag{F.19}$$

Equation F.20 defines the aggregate PTD across all o,d,τ:

$$Y = \sum_{\forall o,d,\tau} Y_{o,d,\tau} n_{o,d,\tau} \tag{F.20}$$

Passenger-miles delivered (PMD) is a distance-weighted measure of throughput based on PTD:

$$Z^{k}_{o,d,\tau} = \frac{\sum_{i \in \dot{\mathrm{I}}^{k}_{o,d,\tau}} s^{k}_{i} x^{k}_{i}}{n^{k}_{o,d,\tau}} \tag{F.21}$$

Equation F.22 finds the average PMD for all trips from o to d starting in interval τ over all operational conditions $k \in K$:

$$Z_{o,d,\tau} = \sum_{k \in K} Z^{k}_{o,d,\tau} p_k \tag{F.22}$$

Equation F.23 defines the aggregate PMD across all o,d,τ:

$$Z = \sum_{\forall o,d,\tau} Z_{o,d,\tau} n_{o,d,\tau} \tag{F.23}$$

For example, in the Dallas ICM Corridor, the simulation period is from 5:30 a.m. to 11:00 a.m., while the peak hours are from 6:30 a.m. to 9:00 a.m. It is anticipated that with or without an ICM strategy in place, all trips that begin in the peak period should be completed before the simulation ends at 11:00 a.m. In this case, there may be little difference in PMT or PMD when 11:00 a.m. is used as the logical time cutoff. To measure the peak capability of the system to deliver trips, the set of trips counting toward PMD could potentially be restricted to those trips that can both begin and complete their trips in the peak period (6:30 a.m. to 9:00 a.m.). At this point, it is premature to define a specific time cutoff for PMD to be applied in all three sites.

Restricting the calculation of measures to selected cohorts is also relevant to the calculation of delay and travel time reliability measures. Although peak periods vary among the AMS sites in terms of the onset and duration of congestion, a consistent set of trips that contribute to measure calculation should be identified. As in the case of the throughput time cutoff point, the U.S. DOT may wish to prescribe specific times in the future.

At this time, it is unclear whether PMT, PMD, or PTD will be the selected performance measure for corridor throughput, pending clarification that all ICM models can support these measures.

Estimation of Travel Times and Travel Distance for Incomplete Trips

Trips that cannot complete their trips by the time that the simulation ends are still included in the calculation of all delay and travel time calculations. Our approach is to estimate total travel time, including any additional time that would be required to complete the trip, given the average speed of travel.

First, let $\ddot{\mathrm{I}}^{0}_{o,d,\tau}$ be the set of $n^{0}_{o,d,\tau}$ trips from origin o, destination d starting a trip in time interval τ that can be completed under the low-demand operational condition used to identify the zero-delay travel times.

The average distance traveled over these trips is:

$$\ddot{\mathrm{X}}^{0}_{o,d,\tau} = \frac{\sum_{i \in \ddot{\mathrm{I}}^{0}_{o,d,\tau}} s^{k}_{i}}{n^{0}_{o,d,\tau}} \tag{F.24}$$

Next, let $\bar{\mathrm{I}}^{k}_{o,d,\tau}$ be the set trips from origin o, destination d starting a trip in time interval τ that *cannot* be completed under operational condition k. For all $i \in \bar{\mathrm{I}}^{k}_{o,d,\tau}$, let $\bar{x}^{k}_{i}$ be the distance traveled on the trip i up to the point where the simulation ends, and let $\bar{t}^{k}_{i}$ the travel time on trip i up to the point where the simulation ends.

Average travel speed for a trip that cannot be completed is expressed in Equation F.25:

$$\bar{v}^{k}_{i} = \frac{\bar{x}^{k}_{i}}{\bar{t}^{k}_{i}} \tag{F.25}$$

Estimated total trip travel time for a trip that cannot be completed before the simulation ends is the accumulated travel time, plus the time to travel the remaining distance at average trip speed:

$$t_i^k = \overleftarrow{t}_i^k + \max\left\{\left(\ddot{X}^0_{o.d.\tau} - \overleftarrow{x}_i^k\right)\overleftarrow{v}_i^k, 0\right\} \tag{F.26}$$

$$x_i^k = \max\left\{\ddot{X}^0_{o.d.\tau}, \overleftarrow{x}_i^k\right\} \tag{F.27}$$

Comparing Pre-ICM and Post-ICM Cases

All of the travel time and throughput measure calculation procedures defined previously are conducted under a single set of simulation settings reflecting a specific set of corridor management policies, technologies, and strategies (here referred to as a case, but often called an alternative). The complete suite of delay, travel time reliability, and throughput measures is calculated independently for each case (e.g., pre-ICM). Comparisons of the resulting measures are then made to characterize corridor performance under each case.

Comparing Observed and Simulated Performance Measures

These few key measures have been defined in detail for national consistency across all AMS sites. Sites have also identified measures. This document has dealt in detail with the calculation of measures from simulation outputs. However, the calculation of comparable measures using observed data demands an equivalent level of detailed attention. These observed measures will be critical in the AMS effort to validate modeling accuracy and in performance measurement in the demonstration phase. Because of the nature of the simulation output, the modeling analyst is able to resolve and track performance at a level of detail that is not available to an analyst working with field counts, speeds, and transit passenger-counter outputs. However, it is the responsibility of the site and the AMS contractor to ensure that these measures are similar in intent, if not in precise calculation. In many cases, the simulation tools or their basic outputs can be manipulated to produce measures quite comparable with field data. An example of this is in throughput calculation, where a site may wish to pursue a screenline passenger throughput measure from field data. In addition to the system-level throughput measures detailed previously, the simulation model can be configured to produce passenger-weighted counts across the same screenline to match the field throughput measure.

G

GUIDANCE TO IMPROVE TSM&O PLANNING AND PROGRAMMING CAPABILITY

TABLE G.1 GUIDANCE TO IMPROVE TSM&O PLANNING AND PROGRAMMING CAPABILITY

	Levels of Capability and Strategies to Improve to Next Level			
Dimension	**Level 1**	**Level 2**	**Level 3**	**Level 4**
1. Organizational Structure and Staffing for TSM&O	Planners with limited TSM&O background	Needed staff capabilities for planning identified and specified	Key relationships and needed capacities established	Formalized TSM&O organizational structure and position descriptions accommodated
	L 1 to L 2 *Identify needed core technical capabilities for all dimensions within individual agencies.* *Review partner agencies/staff relative capabilities.* *Review relationship among agencies' planning staff with operations staff and other units related to operations (maintenance, traffic engineering).* *Identify logical functional coordination and accountability relationships.*	*L 2 to L 3* *Identify capabilities development/acquisition approach (position specifications).* *Review opportunities for capitalizing on interagency sharing and/or external technical support (outsourcing?).* *Implement formal changes in organizational units and reporting relationships to connect planning to TSM&O implementation decisions.*	*L 3 to L 4* *Incorporate appropriate planning staff positions to fulfill responsibilities (identified in other dimensions).* *Access training and peer interchange to improve staff capabilities.*	

(continued)

TABLE G.1 GUIDANCE TO IMPROVE TSM&O PLANNING AND PROGRAMMING CAPABILITY (continued)

	Levels of Capability and Strategies to Improve to Next Level			
Dimension	**Level 1**	**Level 2**	**Level 3**	**Level 4**
2. Planning Cooperation/ Collaboration for TSM&O	No formal planning or programming for TSM&O	TSM&O consideration at individual unit/agency level	Coordination/sharing of multiagency TSM&O planning via existing technical committees	TSM&O integrated into regional interagency multimodal planning (single process)
	L 1 to L 2 *Identify complete range of TSM&O-related entities (transportation, public safety, private) for involvement.* *Identify ongoing planning-related activities as framework for integration of TSM&O (local, regional, statewide).* *Identify key units/players for TSM&O planning/programming in both formal planning and operations units within entities.* *Develop process and organization (committee, task force) for planning/operations staff integration in planning activities utilizing current cooperation mechanism as point of departure.*	*L 2 to L 3* *Identify approaches to interjurisdictional cooperation for each type/scale of planning (region, corridor, etc.).* *Identify unrepresented stakeholder entities for planning application.* *Identify mechanism to engage stakeholders.* *Reconfigure current formal planning committees, etc. (DOT, MPO) to achieve appropriate representation.* *Identify process to routinize needed cooperation.* *Identify opportunities to share burdens within planning process.*	*L 3 to L 4* *Reconfigure current formal planning process to fully incorporate key TSM&O interests (DOT, authorities, public safety, etc.).* *Formalize process for technical recommendations and resource allocation decisions to incorporate TSM&O.* *Review opportunities for cost-sharing among jurisdictions.*	

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TABLE G.1 GUIDANCE TO IMPROVE TSM&O PLANNING AND PROGRAMMING CAPABILITY (continued)

	Levels of Capability and Strategies to Improve to Next Level			
Dimension	**Level 1**	**Level 2**	**Level 3**	**Level 4**
3. TSM&O Goals and Objectives	None related specifically to dealing with improving TSM&O	TSM&O and related objectives understood/ incorporated as agency policy objective	Overall agency policy/objectives/ strategies adjusted to accommodate TSM&O	TSM&O given appropriate agency priority in plan/program
	L 1 to L 2 *Identify current/potential uses of policy in planning and resource allocation for TSM&O.* *Develop relevant examples, business case narratives for reliability related to stakeholders.* *Specify key agency goals and objectives for TSM&O including mobility, safety, environment, sustainability.* *Communicate to policy/planning function.*	*L 2 to L 3* *Identify appropriate objectives for key goals related to TSM&O potential in measurable outcome terms.* *Relate specific objectives/outcomes to relevant TSM&O strategies.* *Incorporate relevant goals and objectives into formal agency commitments.*	*L 3 to L 4* *Include TSM&O-related objectives as formal focus of agency policy and planning.* *Interact with key stakeholders to build support for approach.* *Identify general requirements of other dimensions to support reliability objectives.*	

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TABLE G.1 GUIDANCE TO IMPROVE TSM&O PLANNING AND PROGRAMMING CAPABILITY (continued)

	Levels of Capability and Strategies to Improve to Next Level			
Dimension	**Level 1**	**Level 2**	**Level 3**	**Level 4**
4. TSM&O Performance Measurement	None used for TSM&O planning and programming	Output data reported from monitoring and utilized in TSM&O strategy improvement	Objectives-based outcome measures developed/reported and utilized	Outcome measures incorporated into policy, strategy, and project-level planning
	L 1 to L 2 *Establish agency policy regarding use of performance measures in policy/programming (including FHWA requirements).* *Identify relevant geographic, time scale and network focus.* *Review measures currently available (even though used for other purposes).* *Review use of output data for purposes of intermediate performance indicators (e.g., incident clearance time).* *Develop agency staff consensus to performance measurement among producers/users of information.* *Establish consensus among key stakeholders to use of performance measurement in developing improvement program.*	*L 2 to L 3* *Evaluate agency capability/resources to support development/use of measures by type.* *Identify key objective-related outcome-based performance measures appropriate to both planning and ongoing operations.* *Develop utilization strategy/responsibilities.* *Develop data acquisition plan and methodology for use in planning and evaluation.* *Develop reporting/accountability framework (dashboards), internal and external.* *Apply performance measures for development/evaluation/planning/programming of TSM&O improvements.*	*L 3 to L 4* *Establish acceptance of use of output measures in policy and planning for all investments (capacity, restoration, TSM&O).* *Develop level playing field process for use in formal planning and programming process (STIP, TIP, corridors).* *Use performance measures in strategy improvements including procedures.*	

(continued)

TABLE G.1 GUIDANCE TO IMPROVE TSM&O PLANNING AND PROGRAMMING CAPABILITY (continued)

	Levels of Capability and Strategies to Improve to Next Level			
Dimension	**Level 1**	**Level 2**	**Level 3**	**Level 4**
5. TSM&O Needs/Deficiency Analysis and Forecasting	No analysis of current or anticipated TSM&O shortfalls	Rules of thumb used to identify remediable TSM&O-related deficiencies	TSM&O-related forecasting used to identify future deficiencies and related strategies	Integration of TSM&O within overall forecasting and deficiency analysis
	L 1 to L 2 *Establish agency/partner commitments to use of needs/deficiency thresholds to identify improvements.* *Identify current problem types, networks, and geographic areas of focus and timeframes (immediate, mid-term).* *Adapt/establish sketch-planning rules of thumb to determine relationship of TSM&O-relevant deficiencies to range of available strategies.* *Identify first priority high impact strategy improvements (next steps/low-hanging fruit) including both routine and nonrecurrent event contexts for current conditions.*	*L 2 to L 3* *Adapt/establish sketch-planning rules of thumb to determine future/continuing impacts of both RC (recurring congestion) and NRC (and related impacts) for both current and forecasted traffic.* *Develop approaches appropriate for arterial as well as expressway analysis.* *Identify current specific performance-based deficiencies needs, gaps by network, area and trip context in terms related to conventional TSM&O strategies.* *Explore formal forecasting approach to determine future deficiencies and related strategy payoffs.*	*L 3 to L 4* *Adapt formal systematic approach to forecasting future reliability (NRC-related, post-processing, simulation, etc.).* *Integrate reliability and other TSM&O-related needs/deficiency analysis into approach used to identify all improvements on level playing field basis for both capacity and operations.* *Incorporate new cutting-edge strategic concepts.* *Identify opportunities to standardize inclusions of ITS/TSM&O components in capacity and reconstruction projects.*	

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TABLE G.1 GUIDANCE TO IMPROVE TSM&O PLANNING AND PROGRAMMING CAPABILITY (continued)

	Levels of Capability and Strategies to Improve to Next Level			
Dimension	**Level 1**	**Level 2**	**Level 3**	**Level 4**
6. TSM&O Plan Development	TSM&O improvements committed on opportunistic basis	Budget-constrained evaluation of strategies on jurisdictional basis	Routine life-cycle comparison of TSM&O with capacity strategies	TSM&O integrated into overall agency priority setting, planning, and programming
	L 1 to L 2 *Review focus function of planning activities (statewide vs. regional vs. corridor).* *Establish plan context (scale, focus—region, corridor, etc.).* *Identify current level of investment by strategy, type of cost, jurisdiction, etc.* *Identify both currently utilized and untapped applicable funding sources.* *Develop approach for scenario evaluation including benefit–cost approaches.* *Prepare stand-alone short-term TSM&O plan for relevant time frame including networks and/or corridor-specific plans.*	*L 2 to L 3* *Apply initial performance measures to current needs and deficiency analysis to match TSM&O strategy performance potential.* *Identify scenarios for logical next steps (low cost, minimal impacts).* *Develop and apply analyses and related mechanisms needed for trade-off analysis (modes, capacity/operations, demand management).* *Develop order-of-magnitude cost estimates for key strategy applications: capital, operational, maintenance, and replacement (life cycle).* *Compare TSM&O improvement costs with capacity approaches to needs/deficiencies.* *Prepare time-staged plan, program, and budget for combined TSM&O strategies for application scales as appropriate.*	*L 3 to L 4* *Forecast strategies' potential impact on types/locations of future performance deficiencies.* *Determine relative cost-effectiveness of TSM&O strategies versus capacity strategies for specific needs/deficiencies (short and long terms).* *Integrate TSM&O improvements into unified statewide and formal programming/budgeting process.* *Include capital, staffing, and maintenance costs on life-cycle basis.*	

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TABLE G.1 GUIDANCE TO IMPROVE TSM&O PLANNING AND PROGRAMMING CAPABILITY (continued)

	Levels of Capability and Strategies to Improve to Next Level			
Dimension	**Level 1**	**Level 2**	**Level 3**	**Level 4**
7. TSM&O Implementation and Feedback	Some TSM&O implemented	Performance reviewed on regular basis and applications adjusted	Performance outcomes used to "tune" and expand TSM&O strategies and improve procedures	Real-time operational adjustments to optimize TSM&O synergies
	L 1 to L 2 *Identify key procedure and protocol features that impact individual TSM&O application effectiveness.* *Establish working relationships among planners, TSM&O strategy managers, and field personnel.* *Research and identify the state of the practice regarding systems and technology and field procedures for each application.* *Identify gaps between current TSM&O as applied and state of practice.*	*L 2 to L 3* *Identify processes and resources required to achieve appropriate level of effectiveness for state of the practice for each strategy.* *Based on discussion among key participants, incorporate needed technology, staffing or process improvements into planning process.* *Use available TSM&O output or outcome data to establish process for identifying and tracking impact of improvements.*	*L 3 to L 4* *Establish interagency process to track and analyze performance and define responses and modifications to TSM&O strategies.* *Incorporate analysis of outcome issues into modification of TSM&O strategy applications.*	

RELATED RESEARCH FOR L05

Institutional Architectures to Improve Systems Operations and Management (L06)

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

Evaluating Alternative Operations Strategies to Improve Travel Time Reliability (L11)

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

Establishing Monitoring Programs for Travel Time Reliability (L02)