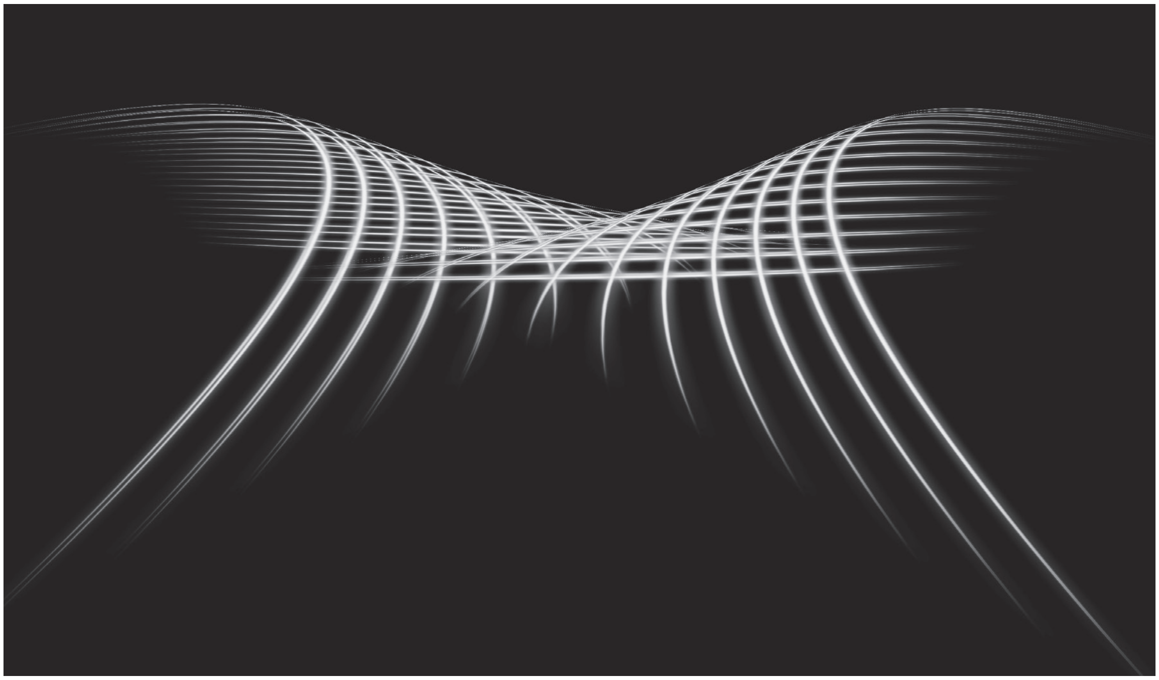
HCM2010

HIGHWAY CAPACITY MANUAL



VOLUME 4: APPLICATIONS GUIDE

TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

WASHINGTON, DC | WWW.TRB.ORG

TRANSPORTATION RESEARCH BOARD 2014 EXECUTIVE COMMITTEE*

Chair: Kirk T. Steudle, Director, Michigan Department of Transportation, Lansing
Vice Chair: Daniel Sperling, Professor of Civil Engineering and Environmental Science and Policy; Director, Institute of Transportation Studies, University of California, Davis
Executive Director: Robert E. Skinner, Jr., Transportation Research Board

Victoria A. Arroyo, Executive Director, Georgetown Climate Center, and Visiting Professor, Georgetown University Law Center, Washington, D.C.
Scott E. Bennett, Director, Arkansas State Highway and Transportation Department, Little Rock
Deborah H. Butler, Executive Vice President, Planning, and CIO, Norfolk Southern Corporation, Norfolk, Virginia (Past Chair, 2013)
James M. Crites, Executive Vice President of Operations, Dallas–Fort Worth International Airport, Texas
Malcolm Dougherty, Director, California Department of Transportation, Sacramento
A. Stewart Fotheringham, Professor and Director, Centre for Geoinformatics, School of Geography and Geosciences, University of St. Andrews, Fife, United Kingdom
John S. Halikowski, Director, Arizona Department of Transportation, Phoenix
Michael W. Hancock, Secretary, Kentucky Transportation Cabinet, Frankfort
Susan Hanson, Distinguished University Professor Emerita, School of Geography, Clark University, Worcester, Massachusetts
Steve Heminger, Executive Director, Metropolitan Transportation Commission, Oakland, California
Chris T. Hendrickson, Duquesne Light Professor of Engineering, Carnegie Mellon University, Pittsburgh, Pennsylvania
Jeffrey D. Holt, Managing Director, Bank of Montreal Capital Markets, and Chairman, Utah Transportation Commission, Huntsville, Utah
Gary P. LaGrange, President and CEO, Port of New Orleans, Louisiana
Michael P. Lewis, Director, Rhode Island Department of Transportation, Providence
Joan McDonald, Commissioner, New York State Department of Transportation, Albany
Abbas Mohaddes, President and CEO, Iteris, Inc., Santa Ana, California
Donald A. Osterberg, Senior Vice President, Safety and Security, Schneider National, Inc., Green Bay, Wisconsin
Steven W. Palmer, Vice President of Transportation, Lowe's Companies, Inc., Mooresville, North Carolina
Sandra Rosenbloom, Professor, University of Texas, Austin (Past Chair, 2012)
Henry G. (Gerry) Schwartz, Jr., Chairman (retired), Jacobs/Sverdrup Civil, Inc., St. Louis, Missouri
Kumares C. Sinha, Olson Distinguished Professor of Civil Engineering, Purdue University, West Lafayette, Indiana
Gary C. Thomas, President and Executive Director, Dallas Area Rapid Transit, Dallas, Texas
Paul Trombino III, Director, Iowa Department of Transportation, Ames
Phillip A. Washington, General Manager, Regional Transportation District, Denver, Colorado

Thomas P. Bostick (Lt. General, U.S. Army), Chief of Engineers and Commanding General, U.S. Army Corps of Engineers, Washington, D.C. (ex officio)
Alison Jane Conway, Assistant Professor, Department of Civil Engineering, City College of New York, New York, and Chair, TRB Young Members Council (ex officio)
Anne S. Ferro, Administrator, Federal Motor Carrier Safety Administration, U.S. Department of Transportation (ex officio)
David J. Friedman, Acting Administrator, National Highway Traffic Safety Administration, U.S. Department of Transportation (ex officio)
LeRoy Gishi, Chief, Division of Transportation, Bureau of Indian Affairs, U.S. Department of the Interior, Washington, D.C. (ex officio)
John T. Gray II, Senior Vice President, Policy and Economics, Association of American Railroads, Washington, D.C. (ex officio)
Michael P. Huerta, Administrator, Federal Aviation Administration, U.S. Department of Transportation (ex officio)
Paul N. Jaenichen, Sr., Acting Administrator, Maritime Administration, U.S. Department of Transportation (ex officio)
Therese W. McMillan, Acting Administrator, Federal Transit Administration, U.S. Department of Transportation (ex officio)
Michael P. Melaniphy, President and CEO, American Public Transportation Association, Washington, D.C. (ex officio)
Gregory G. Nadeau, Acting Administrator, Federal Highway Administration, U.S. Department of Transportation (ex officio)
Cynthia L. Quarterman, Administrator, Pipeline and Hazardous Materials Safety Administration, U.S. Department of Transportation (ex officio)
Peter M. Rogoff, Under Secretary for Policy, U.S. Department of Transportation (ex officio)
Craig A. Rutland, U.S. Air Force Pavement Engineer, Air Force Civil Engineer Center, Tyndall Air Force Base, Florida (ex officio)
Joseph C. Szabo, Administrator, Federal Railroad Administration, U.S. Department of Transportation (ex officio)
Barry R. Wallerstein, Executive Officer, South Coast Air Quality Management District, Diamond Bar, California (ex officio)
Gregory D. Winfree, Assistant Secretary for Research and Technology, Office of the Secretary, U.S. Department of Transportation (ex officio)
Frederick G. (Bud) Wright, Executive Director, American Association of State Highway and Transportation Officials, Washington, D.C. (ex officio)
Paul F. Zukunft (Adm., U.S. Coast Guard), Commandant, U.S. Coast Guard, U.S. Department of Homeland Security (ex officio)

Transportation Research Board publications are available by ordering individual publications directly from the TRB Business Office, through the Internet at www.TRB.org, or by annual subscription through organizational or individual affiliation with TRB. Affiliates and library subscribers are eligible for substantial discounts. For further information, contact the Transportation Research Board Business Office, 500 Fifth Street, NW, Washington, DC 20001 (telephone 202-334-3213; fax 202-334-2519; or e-mail TRBsales@nas.edu).

Copyright 2010 and 2014 by the National Academy of Sciences.
All rights reserved.

Printed in the United States of America.

ISBN 978-0-309-16077-3 [Slipcased set of three volumes]
ISBN 978-0-309-16078-0 [Volume 1]
ISBN 978-0-309-16079-7 [Volume 2]
ISBN 978-0-309-16080-3 [Volume 3]

---

* Membership as of August 2014.

THE NATIONAL ACADEMIES

Advisers to the Nation on Science, Engineering, and Medicine

The **National Academy of Sciences** is a private, nonprofit, self-perpetuating society of distinguished scholars engaged in scientific and engineering research, dedicated to the furtherance of science and technology and to their use for the general welfare. On the authority of the charter granted to it by the Congress in 1863, the Academy has a mandate that requires it to advise the federal government on scientific and technical matters. Dr. Ralph J. Cicerone is president of the National Academy of Sciences.

The **National Academy of Engineering** was established in 1964, under the charter of the National Academy of Sciences, as a parallel organization of outstanding engineers. It is autonomous in its administration and in the selection of its members, sharing with the National Academy of Sciences the responsibility for advising the federal government. The National Academy of Engineering also sponsors engineering programs aimed at meeting national needs, encourages education and research, and recognizes the superior achievements of engineers. C. D. (Dan) Mote, Jr., is president of the National Academy of Engineering.

The **Institute of Medicine** was established in 1970 by the National Academy of Sciences to secure the services of eminent members of appropriate professions in the examination of policy matters pertaining to the health of the public. The Institute acts under the responsibility given to the National Academy of Sciences by its congressional charter to be an adviser to the federal government and, on its own initiative, to identify issues of medical care, research, and education. Dr. Victor J. Dzau is president of the Institute of Medicine.

The **National Research Council** was organized by the National Academy of Sciences in 1916 to associate the broad community of science and technology with the Academy's purposes of furthering knowledge and advising the federal government. Functioning in accordance with general policies determined by the Academy, the Council has become the principal operating agency of both the National Academy of Sciences and the National Academy of Engineering in providing services to the government, the public, and the scientific and engineering communities. The Council is administered jointly by both Academies and the Institute of Medicine. Dr. Ralph J. Cicerone and C. D. (Dan) Mote, Jr., are chair and vice chair, respectively, of the National Research Council.

The **Transportation Research Board** is one of six major divisions of the National Research Council. The mission of the Transportation Research Board is to provide leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied activities annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation. **www.TRB.org**

www.national-academies.org

CHAPTER 36
TRAVEL TIME RELIABILITY

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

Travel time reliability reflects the distribution of travel time of trips using a facility over an extended period of time. The distribution arises from the interaction of a number of factors that influence travel times:

Travel time reliability is influenced by demand variations, weather, incidents, work zones, and special events.

- *Recurring variations in demand,* by hour of day, day of week, and month of year;
- *Severe weather* (e.g., heavy rain, snow, poor visibility) that reduces capacity;
- *Incidents* (e.g., crashes, stalls, debris) that reduce capacity;
- *Work zones* that reduce capacity and that (for longer-duration work) may influence demand; and
- *Special events* (e.g., major sporting events, large festivals or concerts) that produce temporary, intense traffic demands, which may be managed in part by changes in the facility's geometry or traffic control.

The same underlying distribution of travel times can be characterized in two ways, each of which is valid and leads to a set of performance measures that capture the nature of travel time variability:

The travel time distribution can be characterized in terms of travel time variability or in terms of the success or failure of a given trip in meeting a target travel time.

1. Measures of the *variability* in travel times that occur on a facility or a trip over the course of time, as expressed through metrics such as a 50th, 80th, or 95th percentile travel time; and
2. Measures of the reliability of facility travel times, such as the number of trips that *fail or succeed* in accordance with a predetermined performance standard, as expressed through metrics such as on-time performance or percent failure based on a target minimum speed or travel time.

Reliability is quantified from the distribution of travel times on a facility.

For convenience, the remainder of this chapter uses the single term *reliability* for both the variability-based and the reliability-based approaches to characterizing a facility's travel time distribution. A sufficiently long history of travel times is required to establish a facility's travel time distribution—a year is generally long enough to capture most of the variability caused by the factors listed above.

HCM freeway and urban street facility methods describe average conditions in the absence of severe weather and incidents during a defined analysis period; Chapter 36 describes how much conditions can be expected to vary from the average.

The *Highway Capacity Manual*'s (HCM's) freeway and urban street facility procedures (Chapters 10 and 16, respectively) describe average conditions along the facility during a user-defined *analysis period,* typically the peak 15 min of a peak hour, under typical conditions (e.g., good weather, no incidents). Since this value is an average, conditions will be better at certain times of the day or on certain days during the year because of lower-than-average traffic demands. There will also be days when conditions are much worse because of incidents, severe weather, unusually high demand levels, or a combination.

Chapter 36, Travel Time Reliability, presents methods that can be used to describe *how often* particular operational conditions occur and *how bad* conditions can get. This chapter's variability and reliability performance measures can be used as the basis for quantifying the degree of severity of Level of Service (LOS)

F (oversaturated) conditions, for developing agency performance standards for oversaturated facilities, and for quantifying the impacts of physical and operational measures designed to improve travel time reliability.

Because travel time reliability is a new concept for the HCM, this chapter first describes the reliability concept, how reliability can be measured, and how reliability can be applied to analyses to help inform their results:

- The remainder of Section 1 presents definitions of reliability terms along with a high-level overview of the reliability methodology.
- Section 2 presents travel time variability and reliability concepts, including performance measures, illustrative reliability results from U.S. freeway and urban street facilities, potential data sources, and guidance on interpreting reliability results.
- Sections 3 and 4 describe the travel time distribution estimation methods for freeway and urban street facilities, respectively, at a high level. The descriptions omit many computational details. Readers wishing a greater level of detail are referred to Chapter 37, Travel Time Reliability: Supplemental. The cell formulas and Visual Basic macros in the FREEVAL-RL and STREETVAL computational engines, available in the Technical Reference Library in the online HCM Volume 4, provide the greatest level of detail.
- Section 5 presents default values for the methods, describes potential applications (use cases) for reliability analyses, and addresses the role of alternative tools (such as simulation) in evaluating travel time reliability.
- Section 6 provides example problems illustrating the application of the reliability methods to a freeway facility and an urban street facility.
- Section 7 lists the chapter's references.

This chapter describes the reliability methods at a high level. Details are provided in Chapter 37.

Chapter 37, Travel Time Reliability: Supplemental, provides the computational details of the reliability methodologies, presents variability statistics for a number of U.S. freeway and urban street facilities, and provides a method for measuring variability and reliability in the field.

DEFINITIONS

The following terms are used in this chapter:

- **Free-flow speed (freeways).** The average speed of through traffic on the facility under low-flow conditions (see Chapter 9, Glossary). It may be measured from field data as the 85th percentile highest 5-min average speed of vehicles observed traveling the full length of the facility during uncongested periods (for example, 7 to 9 a.m. on nonholiday weekends).
- **Free-flow speed (urban streets).** The average running speed of through automobiles when they travel along a street under low-volume conditions and when they are not delayed by traffic control devices or other vehicles.
- **Travel time.** The time required for a motorized vehicle to travel the full length of the facility from mainline entry to mainline exit points without

leaving the facility or stopping for reasons not related to traffic conditions or traffic control.

- **Travel time index (TTI).** The ratio of the actual travel time on a facility to the theoretical travel time at free-flow speed.
- **Planning time index (PTI).** The ratio of the 95th percentile highest travel time to the theoretical free-flow travel time.
- **Free-flow travel time.** The length of the facility divided by the estimated free-flow speed for the facility.
- **Scenario.** A unique combination of traffic demand, capacity, geometry, and traffic control conditions. It can represent one or more analysis periods, provided that all periods have the same combination of demand, capacity, geometry, and control.
- **Study period.** The time interval (within a day) that is represented by the performance evaluation. It consists of one or more consecutive analysis periods.
- **Analysis period.** The time interval evaluated by a single application of an HCM methodology.
- **Study section.** The length of facility over which reliability is to be computed. Since reliability is computed for through traffic only, the length of the facility should not be so long that through traffic is a low percentage of total traffic on the facility. The length of facility to be evaluated should be less than the distance a vehicle traveling at the average speed can achieve in 15 min.
- **Reliability reporting period.** The specific days over which reliability is to be computed, for example, all nonholiday weekdays in a year.
- **Holidays.** Federal holidays as listed by the General Service Administration for federal workers plus any state and local holidays that may reduce facility demands by 10% or more from average levels.
- **Special event.** Short-term events, such as major sporting events, concerts, and festivals, that produce intense traffic demands on a facility for limited periods of time, which may be addressed by temporary changes in the facility’s geometry or traffic control characteristics, or both.

Other terms not listed above use the definition given in Chapter 9, Glossary.

OVERVIEW OF THE METHODOLOGY

At its core, this chapter’s methodology for estimating the travel time distribution consists of hundreds of repetitions of the freeway and urban street facility methods presented in Chapters 10 and 16, respectively. In contrast to the base HCM facility methods, where the inputs to the model represent average values for a defined analysis period, this chapter’s method varies the demand, capacity, geometry, and traffic control inputs to the facility model with each repetition (*scenario*).

The full range of HCM performance measures output by the facility model are assembled for each scenario and can be used to describe a facility’s performance over the course of a year or other user-defined reliability reporting period. Performance can be described on the basis of a percentile result (e.g., the 80th or 95th percentile travel time) or the probability of achieving a particular level of service (e.g., the facility operates at LOS D during X% of nonholiday weekday hours during the year). Many other variability and reliability performance measures can be developed from the facility's travel time distribution.

This chapter's method is sensitive to the main sources of variability that lead to travel time unreliability:

- *Temporal variability in traffic demand*—both regular variations by hour of the day, day of the week, and month or season of the year and random variations between hours and days;
- *Incidents* that block travel lanes or that otherwise affect traffic operations and thus capacity;
- *Weather events* that affect capacity and possibly demand;
- *Work zones* that close or restrict travel lanes, thus affecting capacity; and
- *Special events* that produce atypical traffic demands that may require management by special traffic control measures.

Input data beyond those needed for an HCM facility analysis consist of demand variation data, incident data, weather data, work zones, and special events. The first three types of data can be defaulted when they are not available locally.

Work zones and special events are location-specific parameters that must be provided by the analyst. Location-specific data related to traffic demand variability, incidents, and weather patterns are best provided by the analyst if they are available; however, this method also provides default values for use when local data are unavailable or the analysis does not require that level of precision.

Scenarios are built from combinations of conditions associated with each source of travel time variability. For example, one scenario could represent demand volumes representative of Fridays in May, fair weather, and one lane closed for 30 min because of an incident that occurs during the p.m. peak hour. A probability of occurrence is associated with each scenario on the basis of local data provided by the analyst or the method's default data and is used to develop a travel time distribution for the reliability reporting period.

The method for estimating the travel time distribution calculates the performance of a series of scenarios representing different combinations of conditions that affect a facility's demand or capacity, or both.

Exhibit 36-1 provides a high-level representation of the methodology for estimating the travel time distribution. The *base dataset* consists of all the data needed to evaluate the base HCM facility method for a single study period, plus data that describe the variations in demand, weather, and so forth that occur over the course of the reliability reporting period, along with the frequency of a particular event's occurrence. The *scenario generator* identifies all possible combinations of demand, weather, incidents, and so forth and creates a set of *scenarios* in which the base facility demand and capacity are adjusted to reflect the changes in demand and capacity that occur under each combination of conditions. Each scenario is given to the *core HCM facility method,* which calculates the facility travel time associated with the scenario. The individual facility travel times are then compiled into the facility's *travel time distribution.* This distribution can be used to develop a variety of reliability and variability *performance measures* for the facility.

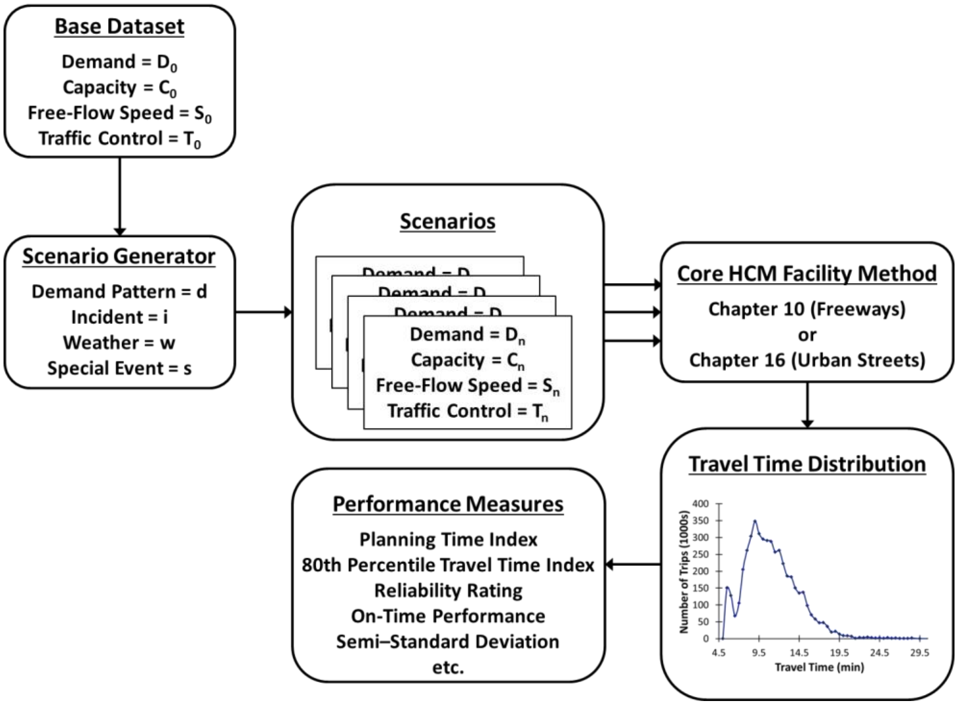


Exhibit 36-1
High-Level Representation of the Method for Estimating the Travel Time Distribution

Because of the hundreds (or even thousands) of scenarios that are generated, implementation of this method is only practical through software. Software automates the scenario generation process, performs the computations associated with the HCM facility method for each scenario, and stores and processes the output performance measures generated for each scenario. Source code listings for research-grade computational engines, FREEVAL-RL and STREETVAL, are provided in the Technical Reference Library in HCM Volume 4 for freeways and urban streets, respectively.

Because hundreds or thousands of scenarios are generated, implementation of the method is only practical through software.

The freeway and urban street methodologies for predicting travel time distributions described in this chapter are based largely on the products of a SHRP 2 project (*1*). Contributions to these methodologies from other research are referenced at relevant points in the chapter.

REQUIRED INPUT DATA

HCM Facility Analysis Input Data

As a starting point, all of the input data normally needed to apply the freeway or urban street facility method are required. These requirements are given in Chapter 10, Freeway Facilities, and Chapter 17, Urban Street Segments. These data are referred to as an *HCM dataset* in this chapter.

For some reliability evaluations, more than one HCM dataset will be required. One HCM dataset, the *base dataset*, is always required and is used to describe base conditions (particularly demand and factors influencing capacity and free-flow speed) when work zones and special events are not present. The base dataset can represent average demand conditions [annual average daily traffic (AADT)] or the demand measured on a specific day. This chapter's methods factor these demands on the basis of user-supplied or defaulted demand patterns to generate demands representative of all other time periods during the reliability reporting period.

Additional HCM datasets are used, as needed, to describe conditions when a specific work zone is present or when a special event occurs. They are called *alternative datasets.* The user must specify any changes in base conditions (e.g., demand, traffic control, available lanes) associated with the work zone or special event, along with the times when the alternative dataset is in effect. For example, if a work zone exists during a given month, an alternative dataset is used to describe average conditions for the analysis period during that month.

Summary of Additional Data Required for a Reliability Evaluation

Additional data (beyond those needed for an HCM facility operations evaluation) are required for a reliability evaluation on a facility. Exhibit 36-2 gives the general categories of data that are required by facility type. Details are provided in the following subsections.

Exhibit 36-2
General Data Categories Required for a Reliability Evaluation

Data Category	Freeways	Urban Streets
Time periods	Analysis period, study period, reliability reporting period.	Analysis period, study period, reliability reporting period.
Demand patterns	Day-of-week by month-of-year demand factors. Can be defaulted.	Hour-of-day (K) factors, day-of-week and month-of-year demand factors relative to AADT. Demand change due to rain and snow. Can be defaulted.
Weather	Probabilities of various intensities of rain, snow, cold, and low visibility by month. Can be defaulted.	Rain, snow, and temperature data by month. Pavement runoff duration for a snow event. Can be defaulted.
Incidents	Probabilities of occurrence of shoulder and lane closures, and average incident durations. Alternatively, crash rate and incident-to-crash ratio for the facility, in combination with defaulted incident type probability and duration data.	Probabilities of specific crash and incident types by location. Alternatively, segment and intersection crash frequencies. Crash frequency adjustment factors. Factors influencing incident duration. The latter two factors can be defaulted.
Work zones and special events	Changes to base conditions (alternative dataset) and schedule.	Changes to base conditions (alternative dataset) and schedule.
Nearest city	Required when defaulted weather data are used.	Required when defaulted weather data are used.
Geometrics	N/A	Presence of shoulder.
Traffic counts	Demand multiplier for demand represented in base dataset.	Day and time of traffic counts used in base and alternative datasets.
Functional class	N/A	Urban street functional class required when defaulted demand patterns are used.

Note: N/A = not applicable.

As shown in Exhibit 36-2, most reliability-specific inputs can be defaulted. Section 5, Applications, provides default values that allow analysts in "data poor" regions lacking detailed demand, weather, or incident data to apply this chapter's methods and obtain reasonable results. At the same time, the method allows analysts in "data rich" regions to provide local data for these inputs when the most accurate results are desired.

Time Periods

Analysis Period

The analysis period is the time interval used for the performance evaluation. For freeway facilities, this value is always 15 min (see page 11-8). For urban street facilities, it can range from 15 min to 1 h, with longer durations in this range sometimes used for planning analyses. A shorter duration in this range is typically used for operational analyses. Additional guidance for determining the analysis period duration is provided in Chapter 16, Urban Street Facilities (see page 16-1).

Shorter analysis periods allow more incidents and weather events to be considered in urban street reliability evaluations.

A shorter analysis period duration is desirable for urban street reliability evaluations because it reduces the minimum event duration threshold and thereby increases the number of incidents and weather events that are included in scenarios. In this regard, the structure of the urban street reliability methodology is such that events that are shorter than one-half of the analysis period duration are ignored (i.e., they will not be recognized in the scenario generation process).

Study Period

The study period is the time interval (within a day) that is represented by the performance evaluation. It consists of one or more consecutive analysis periods. A typical study period is 1.0 to 6.0 h in duration and is stated to represent specific times of the day and days of the week (e.g., weekdays from 4:00 to 6:00 p.m.). If oversaturated conditions occur during the study period, at least the first analysis period should be undersaturated. The maximum study period duration is 24 h.

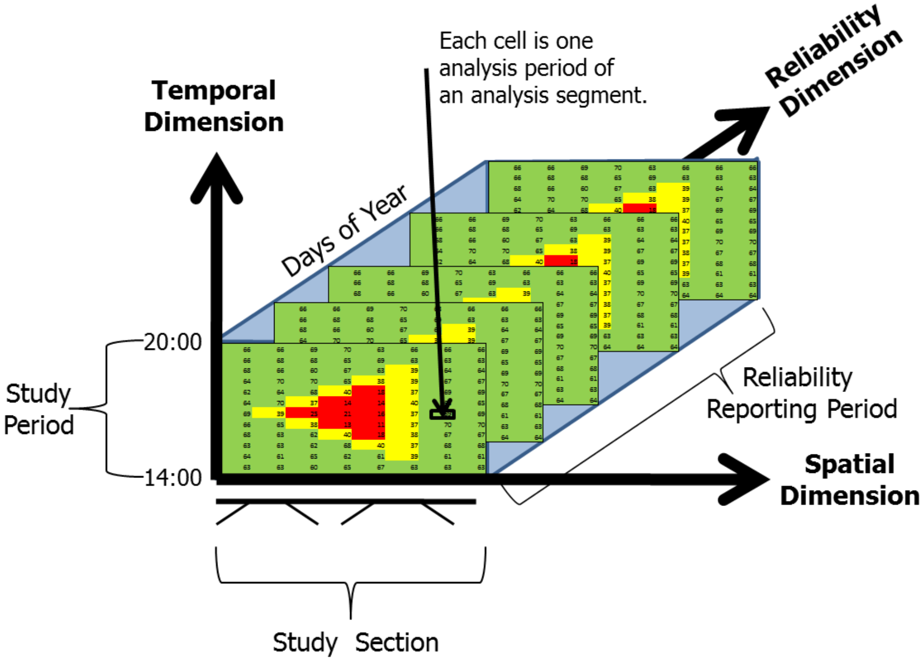
If an urban street facility has two or more time-of-day signal timing plans, a separate study period should be established for each plan period.

The geometric design elements and traffic control features of the facility must be unchanged during this period. Thus, for urban streets, the intersection lane assignments and signal timing plan should be the same throughout the study period. In addition, for urban streets, if the directional distribution of traffic volume changes significantly during the day, separate study periods should be established for each time period where the directional distribution is relatively constant.

Reliability Reporting Period

The reliability reporting period represents the specific days over which the travel time distribution is to be computed. A typical reporting period for a reliability evaluation is 6 to 12 months. The period is specified by start and end dates as well as by the days of week being considered. The reliability reporting period is used with the study period to describe the temporal representation of the performance measure fully (e.g., average travel time on nonholiday weekdays from 4:00 to 6:00 p.m. for the current year). Exhibit 36-3 presents the relationships between the analysis, study, and reliability reporting periods.

Exhibit 36-3
Temporal and Spatial Dimensions of Reliability



Demand Pattern Data

Demand pattern data are used by the reliability method to adjust base demands to reflect demands during all the other portions of the reliability reporting period. Both freeway and urban street facilities require day-of-week and month-of-year variability data. These data can be expressed as ratios of day-of-week and month-of-year demand relative to AADT or as ratios relative to a specified day and month (e.g., Mondays in January). In addition, urban street facilities require hour-of-day factors (*K*-factors) expressed as a percentage of AADT.

The urban street method requires hour-of-day factors because it is designed to start with peak hour demands and expand them to peak period demands. The freeway method starts with peak period demands.

Freeway demand patterns are provided as a 7-day by 12-month matrix, with 84 total values. Urban street demand patterns are expressed as follows:

- Hour-of-day factors for each hour of the study period (up to 24, but typically six or fewer in practice),
- Day-of-week factors for each day included as part of the reliability reporting period (up to seven), and
- Month-of-year factors for each month included as part of the reliability reporting period (up to 12).

The urban street method also allows the user to specify demand adjustment factors for rain and snow conditions.

Default values for freeway and urban street demand are provided in Section 5, Applications. When local data are available (for example, from a permanent traffic recorder station on a freeway), analysts are encouraged to use those data instead, to obtain the most accurate results.

Weather Data

The reliability method uses weather data to adjust the facility's capacity to reflect the effects of weather events on operations. The urban streets method also optionally allows adjustments to demand on the basis of weather conditions. The types of weather data used in the freeway and urban street methods are sufficiently different that they are described separately below.

Freeway Facilities

For convenience, Exhibit 36-4 assigns names to each type of weather event, but the numerical definitions shown are used to determine the capacity- and speed-reducing effects of each event, consistent with Exhibit 10-15 in Chapter 10.

The freeway facility method requires the probabilities of occurrence of 11 specific weather events, with a probability expressed as the fraction of time during the study period for the month that the weather event is present. These weather events correspond to 10 of the weather conditions listed in Chapter 10 (Exhibit 10-15) for which capacity reduction effects of 4% or more have been documented (*2*), plus a "non–severe weather" category encompassing all other types of weather that have no or minimal impact on freeway capacities and speeds. Exhibit 36-4 defines the weather events used for a freeway facility reliability analysis.

In addition to the probabilities of occurrence, an average duration is required for each of the 10 severe weather events.

Exhibit 36-4
Definitions of Freeway Facility Weather Events

Weather Event	Definition
Medium rain	>0.10–0.25 in./h
Heavy rain	>0.25 in./h
Light snow	>0–0.05 in./h
Light–medium snow	>0.05–0.10 in./h
Medium–heavy snow	>0.10–0.50 in./h
Heavy snow	>0.50 in./h
Severe cold	<–4°F
Low visibility	0.50–0.99 mi
Very low visibility	0.25–0.49 mi
Minimal visibility	<0.25 mi
Non–severe weather	All conditions not listed above

The default weather data should be sufficient for most analyses.

Default values have been developed for the probability of occurrence, in each hour of each month, of the 11 types of weather events for 101 metropolitan areas in the United States on the basis of data from 2001 through 2010. Default values have also been developed for the average durations of each type of severe weather event in each area (*3*). The defaults should be sufficient for most analyses; however, analysts are free to substitute more recent or more localized data when they are available.

Urban Street Facilities

An urban streets reliability evaluation requires the weather-related data identified in the following list. These data represent averages by month of year for a recent 10-year period.

- Total normal precipitation (in.),
- Total normal snowfall (in.),
- Number of days with precipitation of 0.01 in. or more (days),
- Normal daily mean temperature (°F), and

- Precipitation rate (in./h).

Default values based on data from 2001 to 2010 are available for each of these statistics for 284 locations in the United States. The defaults should be sufficient for most analyses; however, analysts are free to substitute more recent or more localized data when they are available.

In addition, a *duration of pavement runoff for a snow event* is required. It is defined as the period of time after the snow stops falling that snowpack (or ice) covers the pavement. After this time period elapses, the pavement is exposed and drying begins. This time is likely a function of traffic volume, snow depth, and agency snow removal capabilities. An appropriate local value should be established for the subject facility if that is possible. If such a value is not available, Section 5, Applications, provides a default value for this parameter.

Incident Data

The reliability method uses incident data to adjust the facility's capacity to reflect the effects of shoulder or lane closures. The inputs used in the freeway and urban street methods are sufficiently different that they are described separately below.

Freeway Facilities

A freeway facility reliability analysis requires the monthly probability and average duration of certain incident types. The parameters represent the fraction of time during the study period in each month during which a given incident type occurs. Incident types are defined as no incident, shoulder closure, one-lane closures, two-lane closures, and so forth, up to the number of directional lanes on the facility minus one (i.e., full facility closures are not modeled). The number of incident scenarios depends on the cross section of the *incident segments*, which are defined by the analyst. Up to three incident segments can be defined along the facility, which are ideally located toward the beginning, in the middle, and toward the end of the facility. This approach provides the greatest accuracy, particularly when the effects of treatments to improve facility safety (i.e., reduce the incident rate) or reduce incident duration are being evaluated as part of the analysis.

Full facility closures are not modeled because neither the HCM nor facility-specific alternative tools account for the shift in demand that occurs in such an event.

If incident logs in sufficient detail and duration are not available, the methodology provides a simpler alternative method for estimating the facility incident rate. This approach requires only the following data:

- Local (facility or regional freeway) crash rate per 100 million vehicle miles traveled (VMT),
- Local incident-to-crash-rate ratio, and
- Facility length.

Section 5, Applications, provides default incident duration values that can be applied when this alternative approach is used to estimate the facility incident rate. The effects of treatments to improve facility safety or shorten incident duration, or both, can also be evaluated with the alternative approach, but the analyst should recognize that the method's predicted changes in reliability will be based on changes from national average conditions rather than on local conditions.

Urban Streets

Chapter 16, Urban Street Facilities, defines segments as including portions of their bounding intersections (segments extend from the upstream intersection stop bar to the downstream intersection stop bar). For the purposes of reliability analysis, this definition must be modified to classify collision data by segment or intersection location. For collision data purposes, the classification of whether a collision occurred at the intersection or on the segment is determined by using the definitions given in *Highway Safety Manual* (HSM) Section A.2.3, found in Appendix A of Volume 2 (*4*): "Intersection crashes include crashes that occur at an intersection (i.e., within the curb limits) and crashes that occur on the intersection legs and are intersection-related. All crashes that are not classified as intersection or intersection-related crashes are considered to be roadway segment crashes."

Base Segment and Intersection Crash Frequencies

The methodology predicts noncrash incident frequency, type, and location because most agencies do not have detailed noncrash incident data for urban streets. The method predicts incident frequency as a function of the crash rate. This approach requires supplying base crash frequencies for each segment and intersection along the subject facility. The crash frequencies are an estimate of the expected crash frequency for the segment or intersection when no work zones are present or special events occur. The estimate should include all severity levels, including property-damage-only (PDO) crashes. Crash frequencies are provided in units of crashes per year, regardless of the duration of the reliability reporting period.

Crash Frequency Adjustment Factors for Work Zones and Special Events

One crash frequency adjustment factor for segments and one factor for intersections must be supplied for each work zone or special event for which an alternative dataset is assembled. These factors are used to estimate the expected crash frequency when a work zone or special event is present. The appropriate factor is multiplied by the base crash frequency for the segment or intersection. The result represents the expected crash frequency in a segment or at an intersection if the work zone or special event were present for 1 year.

The factor value should include consideration of the effect of the work zone or special event on traffic volume and crash risk. For example, the volume may be reduced because of diversion, while changes in the roadway geometry and signal operation for a work zone or special event may increase the potential for a crash. To illustrate this concept, consider a work zone that is envisioned to increase crash risk by 100% (i.e., crash risk is doubled) and to decrease traffic volume by 50% (i.e., volume is halved). In this situation, the crash frequency adjustment factor is 1.0 (= 2.0 × 0.5). The analyst's experience with similar types of work zones or special events should be used to determine the appropriate adjustment factor value for the subject facility.

Crash Frequency Adjustment Factors for Inclement Weather

Inclement weather conditions can increase the likelihood of crashes. Crash frequency adjustment factors are required for the following conditions:

- Rainfall,
- Snowfall,
- Wet pavement (not raining), and
- Snow or ice on pavement (not snowing).

Default values for these factors are provided in Section 5, Applications.

Factors Influencing Incident Duration

The time required to clear an incident depends on a number of factors, including time to detect an incident, time to respond, and time to clear the incident. Response and clearance times are weather-dependent; clearance times are also dependent on the incident severity and location (e.g., shoulder versus travel lanes). The following values are required:

- Incident detection time, in minutes, assumed to be generally applicable;
- Incident response times, in minutes, for five weather categories (dry, rainfall, snowfall, wet pavement, snow or ice on pavement); and
- Incident clearance times, in minutes, by street location (segment or intersection), incident type (crash or noncrash), lane location (shoulder, one lane, two or more lanes), severity (fatal/injury or PDO), and weather condition (dry, rainfall, wet pavement, snowfall or snow or ice on pavement) (96 total values).

Default values for these factors are provided in Section 5, Applications. An analyst should supply local values for these factors when the reliability analysis is testing the effects of traffic management measures that influence incident detection, response, or clearance.

Incident Location Distribution

These factors are used by the urban street incident generation procedure to assign incidents to specific locations on the facility. The following incident proportions are required:

- Proportion of crash and noncrash incidents by street location (segment or intersection) (four total values; proportions should total 1.000 for a given street location);
- Proportion of shoulder, one-lane, and two-or-more-lane incidents by street location and event type (crash or noncrash) (12 total values); proportions should total 1.000 for a given street location and event type combination; a 0.000 proportion should be assigned to values involving a shoulder location if no shoulders exist on the facility;
- Proportion of fatal/injury and PDO crashes by street location and lane location (12 total values); proportions should total 1.000 for a given street location and lane location combination; and

- Proportion of breakdown and other noncrash incidents by street location and lane location (12 total values); proportions should total 1.000 for a given street location and lane location combination.

Default values for these factors are provided in Section 5, Applications.

Work Zones and Special Events

Work zones and special events require the use of alternative datasets that specify the demand, geometric, and traffic control conditions in effect during the work zone or special event. A schedule (start and end times each day, along with start and end dates) is also required that specifies when the work zone is in effect or when the special event takes place.

Nearest City

The nearest city is a required input when the analyst chooses to use defaulted weather data. The analyst selects from 101 metropolitan areas for a freeway facility analysis or from 284 locations for an urban street analysis. More locations are available for urban street analysis because this method uses a smaller set of weather data that is available for a larger set of cities.

Geometrics

The presence of outside (i.e., right-side) shoulders is used in the urban street method for predicting incident locations. This input is specified for the facility. The default distribution of incident lane location is based on facilities with outside shoulders. The distribution is modified accordingly when shoulders are not present on the subject facility. For a shoulder to be considered present, it must be wide enough to store a disabled vehicle (so that the vehicle does not block traffic flow in the adjacent traffic lane). If on-street parking is allowed, the analyst will need to determine whether occupancy of the shoulder during the study period is sufficient to preclude its use as a refuge for disabled vehicles. The proportion of on-street parking occupied would need to be less than 30% to provide reasonable assurance of the opportunity to move a disabled vehicle from the through lanes to an open stall.

Traffic Counts

Both the freeway and the urban street methods estimate facility demand in a given scenario by multiplying the base dataset's demand by the day-of-week, month-of-year, and (for urban streets) hour-of-day factors associated with the scenario's demand pattern. These factors were described earlier. However, to apply the appropriate factor, the method needs information concerning what the base dataset demand represents.

The freeway facility method requires a *demand multiplier.* If the supplied demand patterns are relative to AADT, the demand multiplier is the base dataset demand divided by the demand reflective of AADT. If the supplied demand patterns are relative to a specific date, the demand multiplier is the base dataset demand divided by the average demand for that date.

The urban street method requires the date and time of the traffic count used in the base dataset. If the base dataset demands are computed by using planning procedures, they are assumed to represent average day volumes. In this case, a date does not need to be provided by the analyst. However, the time of day for which the estimated volumes apply is still needed.

Functional Class

The functional class of the subject facility is used in the urban street procedure for estimating the traffic volume during each of the various scenarios that make up the reliability reporting period. Specifically, it is used to determine the appropriate traffic volume adjustment factors for each scenario. The following functional classes are considered:

- Urban expressway,
- Urban principal arterial street, and
- Urban minor arterial street.

An urban principal arterial street emphasizes mobility over access. It serves intra-area travel, such as that between a central business district and outlying residential areas or that between a freeway and an important activity center. It is typically used for relatively long trips within the urban area or for through trips that enter, leave, or pass through the city. An urban minor arterial street provides a balance between mobility and access. It interconnects with and augments the urban principal arterial street system. It is typically used for trips of moderate length within relatively small geographic areas (*5*).

Default month-of-year, hour-of-day, and day-of-week adjustment factors are provided for each functional class. The factors are described in Section 5, Applications.

SCOPE OF THE METHODOLOGY

The reliability methodology can be used to evaluate the following sources of unreliable travel time:

- Demand fluctuations,
- Weather,
- Traffic incidents,
- Work zones,
- Special events,
- Inadequate base capacity, and
- Traffic control devices on urban streets.

Demand fluctuations are represented in the methodology in terms of systematic and random demand variation by hour of day, day of week, and month of year. Fluctuations due to diversion are not addressed directly by the methodology but can be optionally provided by the analyst for work zones and special events through the demand specified in an alternative dataset.

LIMITATIONS OF THE METHODOLOGY

Because the reliability methods are based on applying the freeway and urban streets methodologies multiple times, they inherit the limitations of those methodologies, as described in Chapters 10 and 16 through 18, respectively. The reliability methods have additional limitations as described below.

Freeways

The following are limitations of the freeway methodology:

- Weather events that have a small effect on segment capacity reduction (<4%) are not accounted for. A given weather event (e.g., rain, snow) is always assumed to occur at its mean duration value, and only two possible start times for weather events are considered. Sun glare is not accounted for.
- The method assumes that incident occurrence and traffic demand are independent of weather conditions, although all are indirectly tied through the specification of demand, incident, and weather probabilities on a calendar basis.
- Incidents can only occur on three possible segments: the first segment, the segment at the facility midpoint, and the last segment. The timing of the incident is either at the start of a study period or at its midpoint. Finally, only three possible incident durations are considered, the 25th, 50th, and 75th percentiles of the incident duration distribution.
- The methodology does not include the effect of managed lanes on reliability, since the HCM freeway facility method does not address managed lanes.

Urban Streets

In general, the urban street reliability methodology can be used to evaluate the performance of most urban street facilities. However, the methodology does not address some events or conditions:

- Truck pickup and delivery (double parking);
- Signal malfunction;
- Railroad crossing;
- Railroad and emergency vehicle preemption;
- Signal plan transition; and
- Fog, dust storms, smoke, high winds, or sun glare.

Lane or shoulder blockage due to truck pickup-and-delivery activities in downtown urban areas can be considered incidentlike in terms of the randomness of their occurrence and the temporal extent of the event. The dwell time for these activities can range from 10 to 20 min (*6*).

A signal malfunction occurs when one or more elements of the signal system are not operating in the intended manner. These elements include vehicle detectors, signal heads, and controller hardware. A failure of one or more of these elements typically results in poor facility operation.

A railroad crossing the facility at a midsegment location effectively blocks traffic flow while the train is present. Train crossing time can be lengthy (i.e., typically 5 to 10 min) and can result in considerable congestion extending for one or more subsequent analysis periods.

Railroad preemption occurs when a train crosses a cross-street leg of a signalized intersection. The signal operation is disrupted to clear the tracks safely. Signal coordination may be disrupted for several cycles after train clearance.

When a new timing plan is invoked, the controller goes through a transition from the previous plan to the new plan. The transition period can last several cycles, during which traffic progression is significantly disrupted.

Some weather conditions that restrict driver visibility or degrade vehicle stability are not addressed by the methodology. These conditions include fog, dust storms, smoke, and high winds.

2. CONCEPTS

Travel time reliability methods are new to the HCM, and reliability concepts do not appear in Volume 1. Therefore, this section summarizes key reliability concepts. Why an analyst might want to evaluate a facility's reliability is discussed, suggested performance measures and typical values for some common measures are presented, potential data sources for a reliability analysis are identified, and the results of a reliability analysis are interpreted.

OBJECTIVES FOR RELIABILITY ANALYSIS

An important step in any analysis is defining why the analysis is being performed. Key questions or issues should be defined, performance measures that help answer those questions identified, and a basis of comparison for interpreting the analysis results established. Reliability analysis is no different. The following are examples of potential objectives of a reliability analysis:

- Tracking the reliability of a set of facilities in a jurisdiction or region over time to prioritize them for operational or physical treatments,
- Diagnosing the primary causes of the reliability problems on a given facility so that an improvement program can be developed, and
- Evaluating the effects of a particular treatment or improvement on a facility once it has been implemented.

Reliability analysis can be used to improve the operation, planning, prioritization, and programming of transportation system improvement projects.

More broadly, travel time reliability analysis can be used to improve the operation, planning, prioritization, and programming of transportation system improvement projects in the following applications: long-range transportation plans, transportation improvement programs, corridor or areawide plans, major investment studies, congestion management, operations planning, and demand forecasting. The Use Cases portion of Section 5, Applications, describes these applications in greater detail.

PERFORMANCE MEASURES

The reliability methodology produces two types of performance measures: (*a*) distributions of the performance measures produced by the HCM facility methodologies and (*b*) variability and reliability measures based on characteristics of the travel time distribution.

Distributions of HCM Facility Performance Measures

The reliability methodology produces distributions of HCM facility measures that represent their variation during the reliability reporting period. The distributions include percentiles (e.g., 50th percentile speed) and the probability of achieving a particular LOS. For freeway facilities, distributions can be produced for such measures as facility speed, travel time, and average density. For urban streets, distributions can be produced for travel time, travel speed, and spatial stop rate, among others.

Performance Measures Derived from the Travel Time Distribution

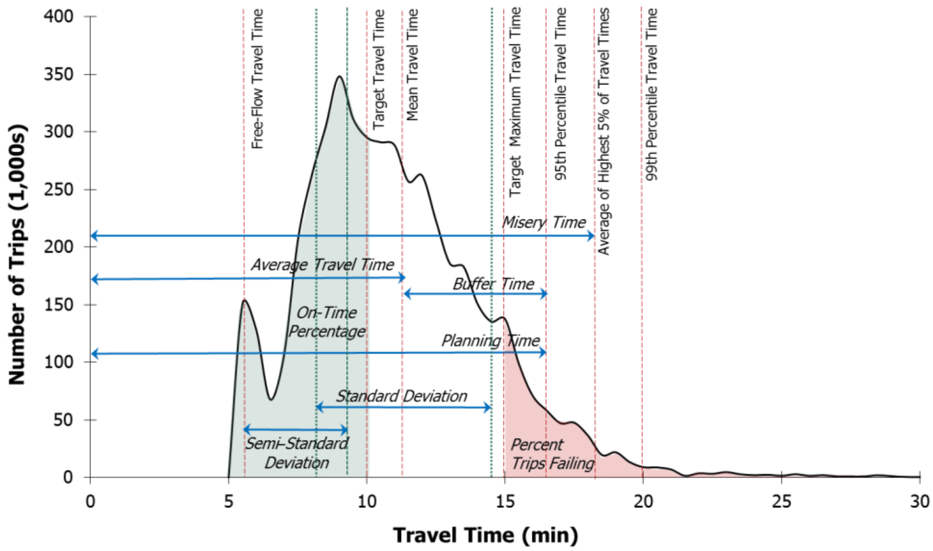
The travel time distribution can be used to derive a variety of performance measures that describe different aspects of reliability:

- *Percentile-based measures,* such as the 95th percentile travel time;
- *On-time measures,* such as the percentage of trips completed within a defined travel time threshold;
- *Failure measures,* such as the percentage of trips that exceed a travel time threshold; and
- *Statistical descriptors of the distribution,* such as standard deviation and kurtosis.

Exhibit 36-5 illustrates how various reliability performance measures can be derived from the travel time distribution. Among these measures are the following:

- *Planning time,* the travel time a traveler would need to budget to ensure an on-time arrival 95% of the time;
- *Buffer time,* the extra travel time a traveler would need to budget, compared with the average travel time, to ensure an on-time arrival 95% of the time; and
- *Misery time,* the average of the highest 5% of travel times (approximating a 97.5% travel time) minus the free-flow travel time, representing a near-worst-case condition.

Exhibit 36-5
Derivation of Reliability Performance Measures from the Travel Time Distribution



To facilitate comparisons of facilities, these measures can be converted into length-independent indices by dividing the base travel time measure by the free-flow travel time. For example, the *misery index* is defined as the misery time divided by the free-flow travel time. The most common index measure is the TTI, which is the ratio of the actual travel time on a facility to the theoretical travel time at free-flow speed. When TTIs are used to describe the travel time distribution, they are often given as a percentile travel time (50th, 80th, and 95th are widely used) or as a mean TTI, when mean travel time is used in the numerator. The 95th percentile TTI is also known as the PTI.

Analysts can also define a *policy index.* That index is similar to the TTI but replaces free-flow speed with a target speed for the facility. The target speed can represent a desired minimum operating speed for the facility (typically chosen as a speed just above breakdown) or an approximation of free-flow speed for use in compiling and comparing results nationally. A related measure is the *reliability rating,* the percentage of trips (or VMT) serviced at a TTI below a defined congestion threshold.

Performance Measures for Reliability Analysis

There are many possible performance measures for quantifying aspects of the travel time reliability distribution. The following are among the more useful measures for quantifying differences in reliability between facilities and for evaluating alternatives to improve reliability.

Measures Describing Typical (Average) Conditions

Typical (or average) conditions are the conditions evaluated by a standard HCM freeway or urban street facility analysis. Useful measures for these conditions include the following:

- *Travel time* (minutes). Travel time is a versatile measure, since it can be monitored over time (for trend analysis), monetized (in calculating benefits), and used in the calculation of other measures (e.g., TTI, delay). Facility lengths usually remain the same over time, allowing apples-to-apples comparisons of travel times estimated for a facility in different years or under different circumstances.
- *50th percentile TTI* (unitless). This measure can be used for trend analysis and to demonstrate changes in performance resulting from an operational strategy, capacity improvement, or change in demand. Because TTI is unitless, it allows facilities to be compared with each other (e.g., for project prioritization purposes or to compare individual facility results with national values, as discussed in the next subsection). The *mean TTI* can also be used for these purposes; this measure will typically have somewhat higher values than the 50th percentile TTI because of the influence of rare, very long travel times in the distribution.
- *Annual delay* (veh-h and p-h). Annual delay represents the average vehicle hours of travel or person hours of travel occurring minus what would occur under free-flow conditions. Delay is useful because economic analyses have a long history of monetizing delay.

Measures Describing Reliability

When travel times are measured or predicted over a long period (e.g., a year), a distribution of travel times results. The following are useful measures for describing (*a*) travel time variability or (*b*) the success or failure of individual trips in meeting a target travel time or speed:

- *PTI* (unitless). This measure is useful for estimating how much extra time travelers must budget to ensure an on-time arrival and for describing near-worst-case conditions on urban facilities.
- *80th percentile TTI* (unitless). This measure has been found to be more sensitive to operational changes than the PTI (*7*), which makes it useful for comparison and prioritization purposes.
- *Failure* or *on-time measures* (percentage). The percentage of trips with space mean speeds above (on time) or below (failure) one or more target values (e.g., 35, 45, and 50 mi/h). These measures address how often trips succeed or fail in achieving a desired travel time or speed.
- *Reliability rating* (percentage). The percentage of trips experiencing a TTI less than 1.33 for freeways and 2.50 for urban streets. These thresholds approximate the points beyond which travel times become much more variable (unreliable). The difference in threshold TTI values is due to differences in how free-flow speed is defined for freeways as opposed to urban streets, since TTI is measured relative to free-flow speed.
- *Semi–standard deviation* (unitless). A one-sided standard deviation, with the reference point at free-flow speed instead of the mean. It provides the variability distance from free-flow conditions.
- *Standard deviation* (unitless). The standard statistical measure.
- *Misery index* (unitless). This measure is useful as a descriptor of near-worst-case conditions on rural facilities.

In many cases, as illustrated in the example problems in Section 6, an analyst may wish to evaluate several of these measures to obtain a complete picture of travel time reliability. However, as a single measure that reflects the traveler point of view by stating the potential for unreliable travel, reporting of the reliability rating is recommended as part of any HCM-based reliability analysis.

TYPICAL TRAVEL TIME VARIABILITY VALUES

Exhibit 36-6 provides percentile ranks of TTI, mean TTI, and PTI for a sampling of U.S. freeways and urban streets compiled by SHRP 2 Project L08 (*1*). The data are values from 2-h a.m. peak, midday, and p.m. peak periods. The process and data used to create this exhibit are described in Section 1 of Chapter 37, Travel Time Reliability: Supplemental.

The databases used to develop this table are relatively small, and whether a larger database would produce similar percentile values is unknown. Although the table is intended as an aid to analysts in comparing a given facility's performance with that of other U.S. facilities, caution is needed in comparing a facility's operation with that of those shown in these exhibits. The analyst's facility may have characteristics different from those of the sample of facilities.

These data are derived from field measurements. Note that the urban street values of TTI and PTI are calculated by using a base travel speed, defined as the 85th percentile speed during off-peak conditions, rather than a free-flow speed. This is because the field-measured travel times include the effects of traffic control devices under low-volume conditions, whereas the HCM definition of free-flow speed specifically omits the effects of traffic control devices.

An HCM-estimated TTI can be converted to a field-measured TTI by multiplying the HCM TTI by the field-measured free-flow speed and dividing by the HCM free-flow speed.

As an example of how to read Exhibit 36-6, assume that the PTI for a freeway for the a.m. peak period has been measured. The PTIs of the selected freeways included in Exhibit 36-6 ranged from 1.53 to 3.92 during the a.m. peak period. Half of these facilities had PTIs less than 1.53, and only 5% of them had PTIs greater than 3.92 (i.e., 95% had PTIs less than 3.92).

Exhibit 36-6
Rankings of Selected U.S. Facilities by TTI, Mean TTI, and PTI

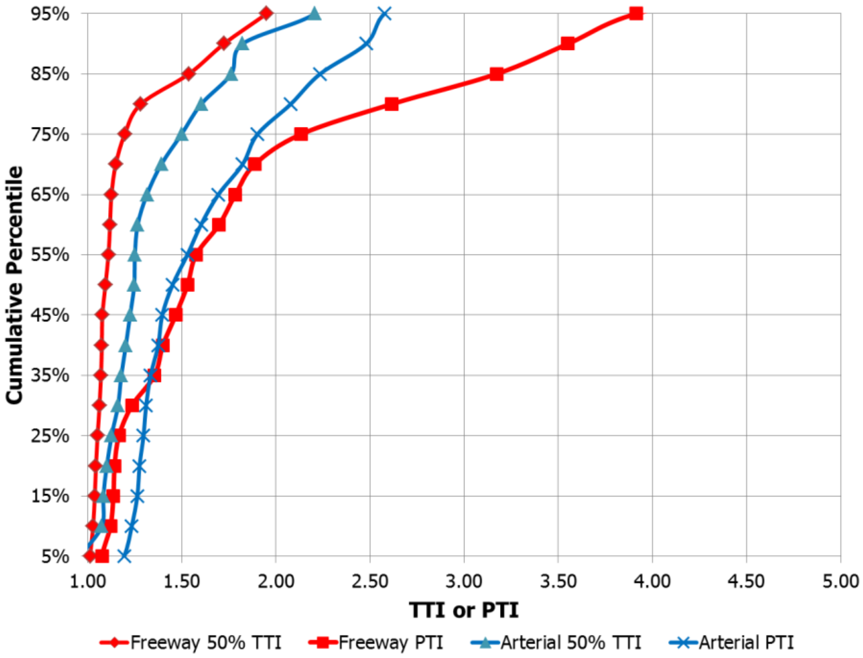
	Freeways			Urban Streets		
Percentile Rank	**TTI**	**Mean TTI**	**PTI**	**TTI**	**Mean TTI**	**PTI**
A.M. PEAK PERIOD						
Worst 5%	1.95	2.08	3.92	1.35	1.36	1.84
Worst 10%	1.72	1.93	3.55	1.28	1.31	1.71
Worst 15%	1.54	1.83	3.17	1.26	1.29	1.66
Worst 20%	1.28	1.48	2.61	1.26	1.29	1.57
Worst 50%	1.09	1.17	1.53	1.20	1.23	1.41
MIDDAY						
Worst 5%	1.21	1.46	3.16	1.35	1.42	1.86
Worst 10%	1.17	1.42	2.85	1.33	1.38	1.63
Worst 15%	1.16	1.32	2.41	1.32	1.35	1.63
Worst 20%	1.14	1.30	1.92	1.31	1.34	1.60
Worst 50%	1.06	1.12	1.32	1.22	1.24	1.45
P.M. PEAK PERIOD						
Worst 5%	1.76	1.99	3.54	1.56	1.60	2.10
Worst 10%	1.70	1.86	3.26	1.49	1.56	1.88
Worst 15%	1.61	1.71	2.93	1.41	1.52	1.83
Worst 20%	1.35	1.57	2.77	1.41	1.49	1.78
Worst 50%	1.17	1.31	1.85	1.25	1.28	1.49

Source: Derived from values given in Chapter 37, Section 1. Entries are the lowest value for a category.

Notes: TTI = travel time index (50th percentile travel time divided by base travel time).
Mean TTI = mean travel time index (mean travel time divided by base travel time).
PTI = planning time index (95th percentile travel time divided by base travel time).
For freeways, the base travel time is the free-flow travel time. For urban streets, the base travel time corresponds to the 85th percentile highest speed observed during off-peak hours.

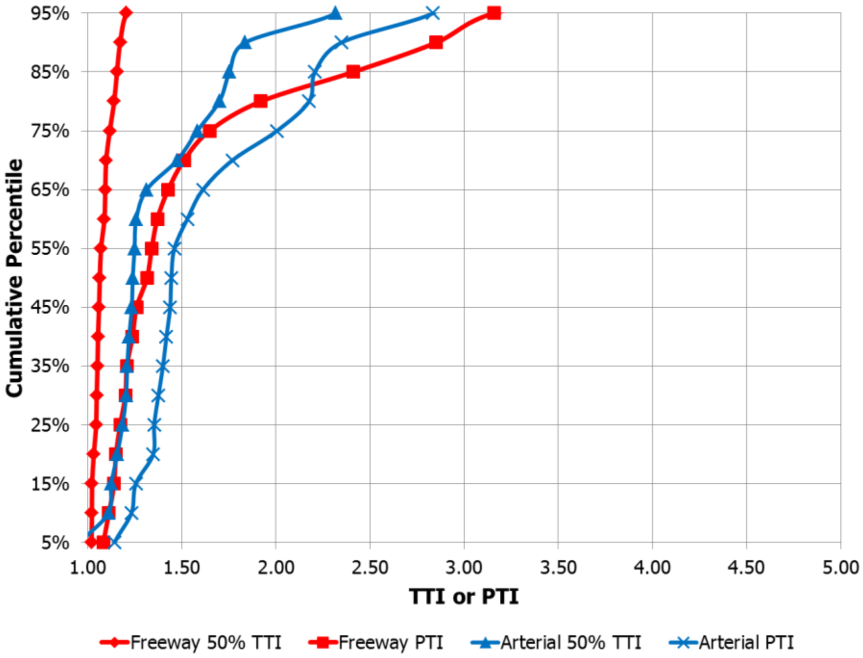
Exhibit 36-7 through Exhibit 36-9 illustrate the distribution of TTI and PTI from the sample of freeways and urban streets. The exhibits indicate that a greater range of unreliable conditions is observed on freeways than on urban streets, as measured by the spread between the most reliable and the least reliable facilities included in the dataset.

Exhibit 36-7
TTI and PTI Distribution on U.S. Freeways and Urban Streets (A.M. Peak Period)



Notes: TTI = travel time index (50th percentile travel time divided by base travel time).
PTI = planning time index (95th percentile travel time divided by base travel time).
For freeways, the base travel time is the free-flow travel time. For urban streets, the base travel time corresponds to the 85th percentile highest speed observed during off-peak hours.

Exhibit 36-8
TTI and PTI Distribution on U.S. Freeways and Urban Streets (Midday Period)



Notes: TTI = travel time index (50th percentile travel time divided by base travel time).
PTI = planning time index (95th percentile travel time divided by base travel time).
For freeways, the base travel time is the free-flow travel time. For urban streets, the base travel time corresponds to the 85th percentile highest speed observed during off-peak hours.

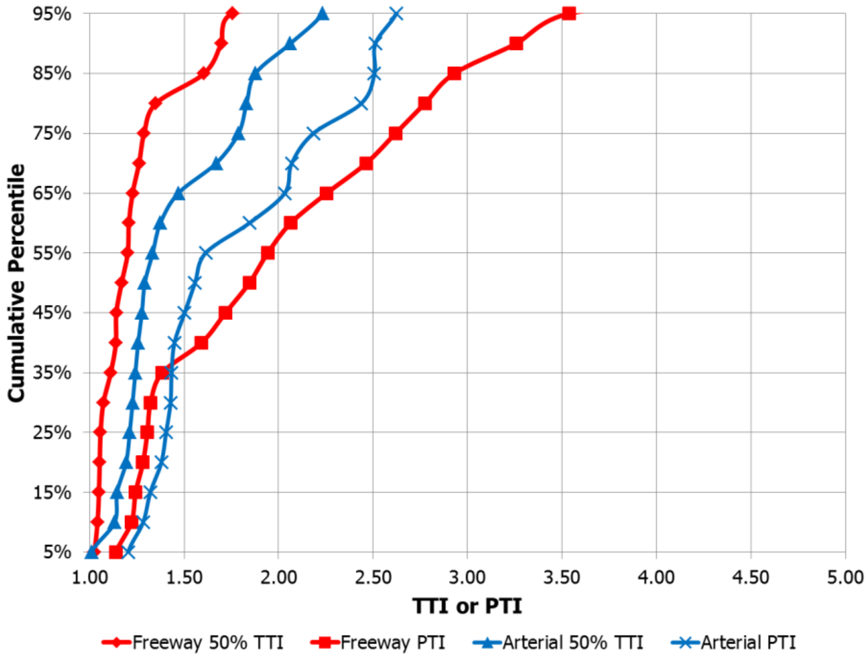


Exhibit 36-9
TTI and PTI Distribution on U.S. Freeways and Urban Streets (P.M. Peak Period)

Notes: TTI = travel time index (50th percentile travel time divided by base travel time).
PTI = planning time index (95th percentile travel time divided by base travel time).
For freeways, the base travel time is the free-flow travel time. For urban streets, the base travel time corresponds to the 85th percentile highest speed observed during off-peak hours.

DATA ACQUISITION

Although default values are provided for many of the variables that affect facility reliability (see Section 5, Applications), the preceding section illustrates that reliability (as measured by TTI or PTI) can vary widely, depending on the characteristics of a particular facility. Therefore, analysts are encouraged to use local values representative of local demand, weather, and incident patterns when the data are available. In addition, analysts must supply local values for work zones and special events if they wish to account for these effects in a reliability analysis. This subsection identifies potential sources of these data.

Demand Patterns

The best potential source of demand pattern data is a permanent traffic recorder (PTR) located along the facility. Alternatively, an analyst may be able to use data from a PTR located along a similar facility in the same geographic area. Many state departments of transportation produce compilations of data from their PTRs and provide demand adjustment factors by time of day, day of week, and month of year by facility and area type. The analyst is reminded that measured volumes are not necessarily reflective of demands. As was illustrated in Exhibit 3-8 (page 3-9), upstream bottlenecks may limit the volume reaching a PTR or other observation point.

Weather

The National Climatic Data Center (NCDC) provides rainfall, snow, and temperature statistics for thousands of locations through its website (*8*) and average precipitation rate data in the *Rainfall Frequency Atlas* (*9*). The more detailed hourly weather data needed for a freeway facility analysis are available from larger airport weather stations and can be obtained from the NCDC website or other online sources (e.g., *3*).

A weather station that a transportation agency has installed along the study facility may also be able to provide the required data, if the agency stores and archives the data collected by the station. A 10-year weather dataset is desirable for capturing weather events that are rare but have a high impact.

Finally, analysts should consider the location of the facility relative to the weather station. Elevation differences, proximity to large bodies of water, and other factors that create microclimates may result in significant differences in the probabilities of certain types of weather events (e.g., snow, fog) on the facility and at the weather station.

Incidents

Freeways

A significant level of effort is required to extract information about the numbers and average durations of each incident type from the annual incident logs maintained by roadway agencies, even in data-rich environments. Furthermore, certain incident types—particularly shoulder incidents—can be significantly underreported in incident logs (*1*). Thus, the direct approach of estimating incident probabilities is reserved for those rare cases where the incident logs are complete and accurate over the entire reliability reporting period.

An alternative approach is to estimate the facility incident rate from its predicted crash rate and assume that the number of incidents in a given study period is Poisson distributed (*10*, *11*). Details of the process are described in Chapter 37, Travel Time Reliability: Supplemental.

Urban Streets

The expected crash frequency can be computed with the predictive method in Chapter 12 of the 2010 HSM (*4*). If this method cannot be used, the expected crash frequency of the subject segment or intersection can be estimated on the basis of its 3-year crash history. Crashes that occur when work zones and special events are present should be removed from the crash data. In this situation, the expected crash frequency is computed as the count of crashes during times when work zones and special events are not present divided by the time period when work zones and special events are not present. Thus, if 15 crashes were reported during a recent 3-year period and five of them occurred during a 6-month period when a work zone was present, the expected crash frequency is estimated as 4.0 crashes per year [= (15 – 5)/(3 – 0.5)]. A technique for distinguishing between segment- and intersection-related crashes is described in Appendix A of Part C of the 2010 HSM (*4*).

Work Zones

A schedule of long-term work zones indicating the days and times when the work zone will be in force and the portions of the roadway that will be affected should be obtained from the roadway operating agency. Work zones that vary in intensity (e.g., one lane closed on some days and two lanes closed on others) or that affect different segments at different times will need to be provided as separate alternative datasets. When detailed traffic control plans for each work zone are available, they should be consulted to determine the starting and ending locations of lane closures, along with any reductions in the posted speed. When detailed plans are not available, the agency's standard practices for work zone traffic control can be consulted to determine the likely traffic control that would be implemented, given the project's characteristics.

Special Events

Special events are short-term events, such as major sporting events, concerts, and festivals, that produce intense traffic demands on a facility for limited periods. Special traffic control procedures may need to be implemented to accommodate the traffic demands. The analyst should identify whether any events that occur in or near the study area warrant special treatment. If so, a schedule for the event (dates, starting times, typical durations) should be obtained. Some types of events also have varying intensities that will require separate treatment (e.g., a sold-out baseball game compared with a lower-attendance midweek game). Recurring events may have developed special traffic control procedures; if so, these plans should be consulted to identify any changes required from base conditions. Alternative datasets will be needed for each combination of special event venue and event intensity.

INTERPRETING RESULTS

Identifying Reliability Problems

In a perfect world, every freeway and urban street facility would be perfectly reliable. They would have mean TTIs and PTIs of 1.00 or better. Since operating a perfectly reliable facility is not a realistic standard, an agency must distinguish between less than perfect—but still acceptable—reliability and unacceptable reliability. This is obviously a choice that each agency must make. This section provides guidance on the factors and criteria that a transportation agency may wish to consider in making its selection, but the final decision is up to the agency.

Criterion No. 1: How Does Reliability Compare with Agency Congestion Management Policy?

If the agency has a policy of delivering a certain minimum speed or maximum travel time on its freeways or urban streets or a maximum acceptable delay per signal or per mile, either the computation of the reliability statistics can be modified on the basis of this information or the reliability statistics can be translated into delays so that failures to meet agency policy can be identified more quickly.

Minimum Speed Policy

If the agency has a minimum acceptable facility speed policy, this information can be used to compute the reliability statistics instead of the free-flow speed. Determining the extent to which the facility meets the agency's target performance level by comparing the computed reliability statistic with the target value of 1.00 is then relatively easy. The result of using the policy speed instead of the free-flow speed is to neglect travel time reliability when speeds exceed the agency's minimum acceptable threshold.

Equation 36-1

$$TTI_{\text{policy}} = \frac{\text{mean travel time}}{\text{policy travel time}}$$

$$PTI_{\text{policy}} = \frac{\text{95th percentile travel time}}{\text{policy travel time}}$$

where

TTI_{policy} = policy travel time index, based on the agency's policy (or target) travel time for the facility (unitless);

PTI_{policy} = policy planning time index, based on the agency policy (or target) travel time for the facility (unitless);

mean travel time = observed mean travel time for through trips on the facility over the reliability reporting period (min);

95th percentile travel time = 95th percentile highest observed through trip travel time on the facility over the reliability reporting period (min); and

policy travel time = agency's maximum acceptable travel time for through trips on the facility (min), determined by dividing the facility length by the minimum acceptable average speed for the facility and converting from hours to minutes.

For example, if the agency's congestion management policy is to deliver freeway speeds in excess of 40 mi/h, the policy travel times are computed by using the facility length divided by 40 mi/h and converting the result to minutes.

Values of 1.00 or less for TTI_{policy} mean that the agency's congestion management policy is being met on average over the course of the reliability reporting period. Values greater than 1.00 mean that the facility is failing to meet the agency's policy on average.

Values of 1.00 or less for PTI_{policy} mean that the agency's congestion management policy is being met at least 95% of the time for the reliability reporting period. Values greater than 1.00 mean that the facility is meeting the agency's policy less than 95% of the time.

Maximum Acceptable Delay

If the agency has a maximum acceptable delay standard per mile (for freeways or urban streets) or per signal (for urban streets), the mean TTI and PTI can be readily converted into equivalent delay estimates for the facility and compared with the agency standard.

$$\text{Average delay per trip} = 3{,}600 \times \frac{\text{Length}}{FFS} \times (TTI_{\text{mean}} - 1)$$

$$\text{Average delay per mile} = 3{,}600 \times \frac{1}{FFS} \times (TTI_{\text{mean}} - 1)$$

$$\text{Average delay per signal} = 3{,}600 \times \frac{\text{Length}}{NS \times FFS} \times (TTI_{\text{mean}} - 1)$$

Equation 36-2

where

TTI_{mean} = travel time index, the mean travel time divided by the free-flow travel time for the facility (unitless);

FFS = average facility free-flow speed, including signal delay at low volumes (mi/h);

Length = facility length (mi); and

NS = number of signals within study section of facility (unitless).

Average delay is the average delay per vehicle in seconds.

For the 95th percentile delay per trip, per mile, and per signal, substitute PTI, the 95th percentile travel time divided by the free-flow travel time for the facility (unitless), for TTI_{mean} in Equation 36-2. These equations can be solved for TTI_{policy} or PTI_{policy} instead of TTI_{mean} to determine the maximum acceptable values of these indices consistent with the agency's maximum delay policy.

Criterion No. 2: How Does Reliability Compare with Other Facilities?

This approach is the most straightforward way to identify levels of acceptable and unacceptable reliability. The agency ranks the reliability results for a given facility against those of other facilities it operates and prioritizes improvements to its facilities with the worst reliability accordingly. Of course, this approach requires that the agency collect reliability data for its facilities so that the agency's facility investments can be properly ranked according to need.

Until an agency has assembled sufficient data on the reliability of its own facilities, it may choose to use Exhibit 36-6, which provides reliability statistics constructed for a relatively small sample of freeways and urban streets in the United States. For example, if an agency's goal is to not have facilities in the worst 5% ranking in the sample, its TTI_{mean} goals would be 1.97 or less for freeways and 1.53 or less for urban streets. Its PTI goals for acceptable reliability would be less than 3.60 for freeways and less than 1.94 for urban streets.

Criterion No. 3: How Does Reliability Compare with HCM LOS?

This criterion involves translating reliability results into more traditional HCM LOS results that decision makers may be more comfortable with. The reliability results are used to identify what percentage of time a facility is operating at an unacceptable LOS and determining a percentage of time that is unacceptable.

For example, the agency's standard may be LOS D. The reliability results may show that the facility operates at LOS E or worse during 5% of the weekday peak periods over the course of a year. This may be an acceptable risk for the agency if the costs of improvements to eliminate the 5% risk are high.

Translating PTI Results into HCM LOS for Freeways

The PTI provides the ratio of the 95th percentile travel time to the free-flow travel time. This value can be translated into the equivalent HCM LOS by converting the PTI to equivalent mean speed, converting the speed to the equivalent density, and looking up the LOS range for the freeway:

Equation 36-3

$$S_{95} = \frac{FFS}{PTI}$$

where

S_{95} = 95th percentile lowest speed for the facility, the speed that is exceeded 95% of the time on the facility over the reliability analysis reporting period (mi/h);

PTI = planning time index for the facility (unitless); and

FFS = facility free-flow speed (mi/h).

The density is compared with the values in Exhibit 10-7 to determine whether the facility will operate at an acceptable LOS at least 95% of the time.

The freeway speed–flow equation (Equation 25-1) is solved for volume and divided by the 95th percentile speed to obtain the equivalent density at that speed.

Equation 36-4

$$D_{F,95} = \frac{c}{S_{95}} \times \frac{\ln[1 + FFS - S_{95}]}{\ln\left[1 + FFS - \frac{c}{45}\right]}$$

where

$D_{F,95}$ = facility density at a speed of $S(95\%)$ (pc/mi/ln),

S_{95} = 95th percentile lowest speed for the facility over the reliability reporting period (mi/h),

FFS = facility free-flow speed, and

c = facility per lane capacity (pc/h/ln).

Note that the 95th percentile lowest speed must be equal to or less than the free-flow speed or there is the risk of exceeding the limits of the logarithm function.

Once the density is computed, the equivalent LOS can be obtained from Exhibit 10-7.

Translating PTI Results into HCM LOS for Urban Streets

The PTI provides the ratio of the 95th percentile highest travel time to the free-flow travel time. This can be translated into the equivalent HCM LOS by converting the PTI to equivalent mean speed. The equivalent percent free-flow speed is simply the inverse of the PTI:

Equation 36-5

$$SR_{95} = 1/PTI$$

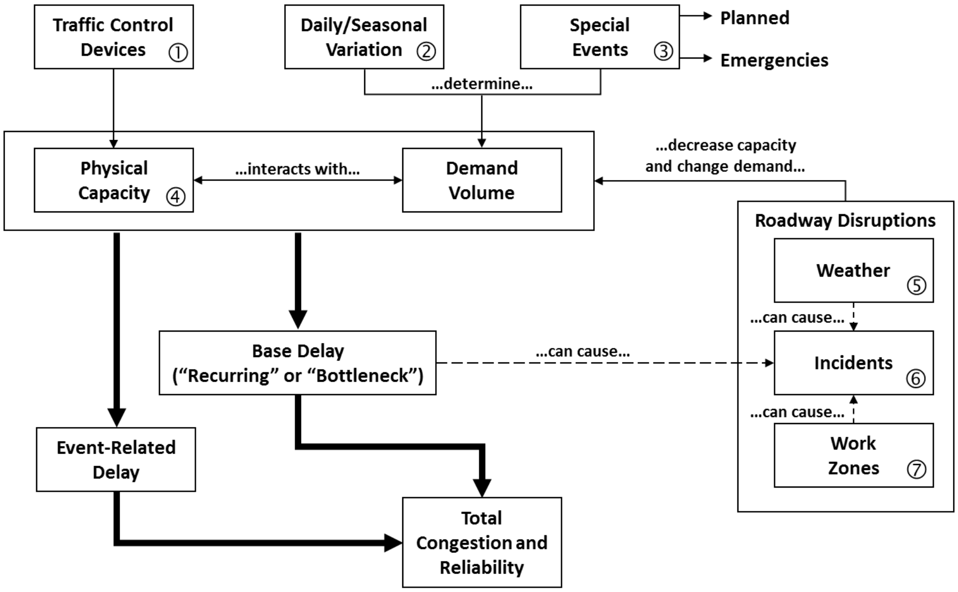
where PTI is the planning time index for the facility and SR_{95} is the 95th percentile speed ratio (unitless): the 95th percentile slowest through trip speed on the facility (including control delay) divided by the HCM-defined free-flow speed, which by definition does not include control delay. The 95th percentile speed ratio is compared with the urban street LOS criteria in Exhibit 16-4 to determine whether the facility will operate at a LOS acceptable to the agency at least 95% of the time.

Diagnosing the Causes of Reliability Problems

Exhibit 36-10 identifies seven sources of congestion and unreliability and shows how they interact with each other. The starting point in traditional analysis is to take a fixed capacity and a fixed volume to develop an estimate of delay, usually for "typical" conditions. However, in the field both physical capacity and demand vary because of roadway disruptions, travel patterns, and traffic control devices. These conditions not only decrease available capacity or cause volatility in demand but also interact with each other. For example, both inclement weather and work zones can lead to an increase in incidents.

Thus, diagnosing the relative contribution of different causes of unreliability involves identifying the causes individually and in combination. Depending on the purpose of the evaluation, various approaches may be taken for assigning the proportional responsibility to individual causes when two or more are acting in combination.

Exhibit 36-10
Interrelationship Between Causes of Congestion and the Facility



Selecting a Performance Measure

To identify the relative effects of different causes on the travel time reliability of the facility, it is recommended that total vehicle (or person) hours of delay summed over the entire reliability reporting period be computed. This measure of effectiveness takes into account both the severity of the event (demand surge, incident, weather) and its frequency of occurrence within the reliability reporting period. Exceptionally severe but rare events may add relatively little to the total annual delay experienced by the facility. Moderate but frequent events will often have a greater effect on total annual delay.

Generating a Simplified Matrix of Causes

Identifying patterns of results in several thousand scenarios is impractical, so it is recommended that the analyst consolidate the many scenarios into a matrix of congestion causes along the lines of Exhibit 36-11. This is best done by combining similar scenarios that individually contribute less than 1% to annual delay. In the example shown in Exhibit 36-11, because severe weather is relatively infrequent at this site, the numerous severe weather events (rain, snow, etc.) have been consolidated into a single "bad weather" category. The results from the original analysis of multiple demand levels have similarly been consolidated into three levels (low, medium, high).

Exhibit 36-11
Example Matrix Allocating Annual Vehicle Hours of Delay by Cause

	Low Demand		**Moderate Demand**		**High Demand**		
Incidents	**Fair Weather**	**Bad Weather**	**Fair Weather**	**Bad Weather**	**Fair Weather**	**Bad Weather**	**Total**
None	596 (2%)	407 (1%)	818 (3%)	362 (1%)	6,240 (23%)	956 (4%)	9,379 (34%)
1 lane closed	2,363 (9%)	92 (<1%)	2,097 (8%)	61 (<1%)	9,102 (33%)	119 (<1%)	13,834 (51%)
2 lanes closed	194 (1%)	13 (<1%)	189 (1%)	9 (<1%)	907 (3%)	17 (<1%)	1,329 (5%)
3 lanes closed	621 (2%)	40 (<1%)	468 (2%)	23 (<1%)	1,510 (6%)	32 (<1%)	2,694 (10%)
Total	3,774 (14%)	552 (2%)	3,572 (13%)	455 (2%)	17,759 (65%)	1,124 (4%)	27,236 (100%)

Diagnosing Primary Causes of Unreliability

The diagnosis proceeds by first examining the cells of the matrix to identify those with the largest annual delay values. For example, examination of the cells in Exhibit 36-11 yields the following conclusions:

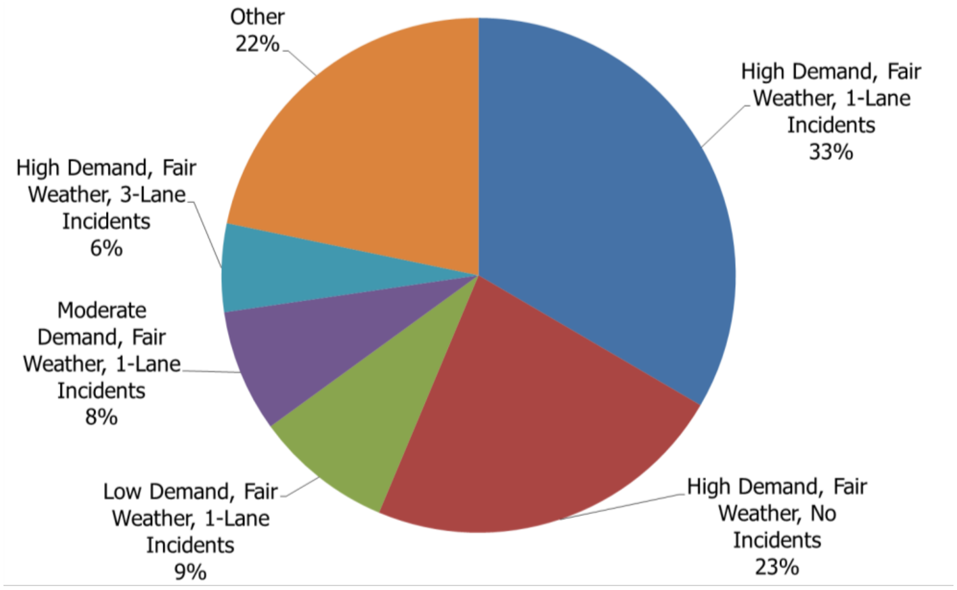
- The single greatest cause of annual delay on the example facility is incidents closing a single lane under high-demand conditions on fair-weather days. They account for 33% of the annual delay on the facility.
- The next largest occurrence of annual delay happens under high-demand, fair-weather, no-incident conditions. They account for 23% of the annual delay on the facility.
- The third and fourth largest annual delays occur when incidents close a single lane under fair-weather conditions with low- to moderate-demand conditions. Together, these scenarios account for 17% of the annual delay on the facility.
- The fifth largest annual delays are accumulated when incidents close three lanes under high-demand and fair-weather conditions.

Exhibit 36-12 shows that the top five cells in Exhibit 36-11 account for about 78% of the annual delay on the facility.

The next step is to examine the row and column totals to determine whether a single cause stands out. For example, examination of the row and column totals in Exhibit 36-11 yields the following conclusions:

- The highest row or column total annual delay occurs in high-demand, fair-weather conditions. Recurring congestion is therefore a significant source of delay on this example facility. High-demand conditions account for 65% of the annual delay on the facility.
- The next highest row or column total occurs when incidents close one lane on the facility. Incidents blocking a single lane account for 51% of the delay on the facility.
- Bad weather is a minor cause of annual delay on the facility.

Exhibit 36-12
Example Pie Chart of Congestion Causes



Developing a Treatment Plan

The conclusions from the example shown in Exhibit 36-11 suggest the following options that are likely to have the greatest effect on improving reliability in the example facility:

- Measures to reduce high-demand conditions or to increase capacity to address recurring congestion, and
- Measures to manage incidents that close a single lane.

The diagnostic process also indicates that in this example, bad weather and extreme incidents (closures of two or more lanes), despite their severity when they happen, are infrequent enough to be minor contributors to total annual delay on the facility.

The particular example used here was from a state with relatively mild weather. The results would likely be different on facilities in other parts of the country.

3. FREEWAY FACILITY METHODOLOGY

OVERVIEW

This section describes the methodology for evaluating the reliability of a freeway facility. It also describes extensions to the base HCM freeway facility method (Chapter 10) that are required for computing reliability performance measures.

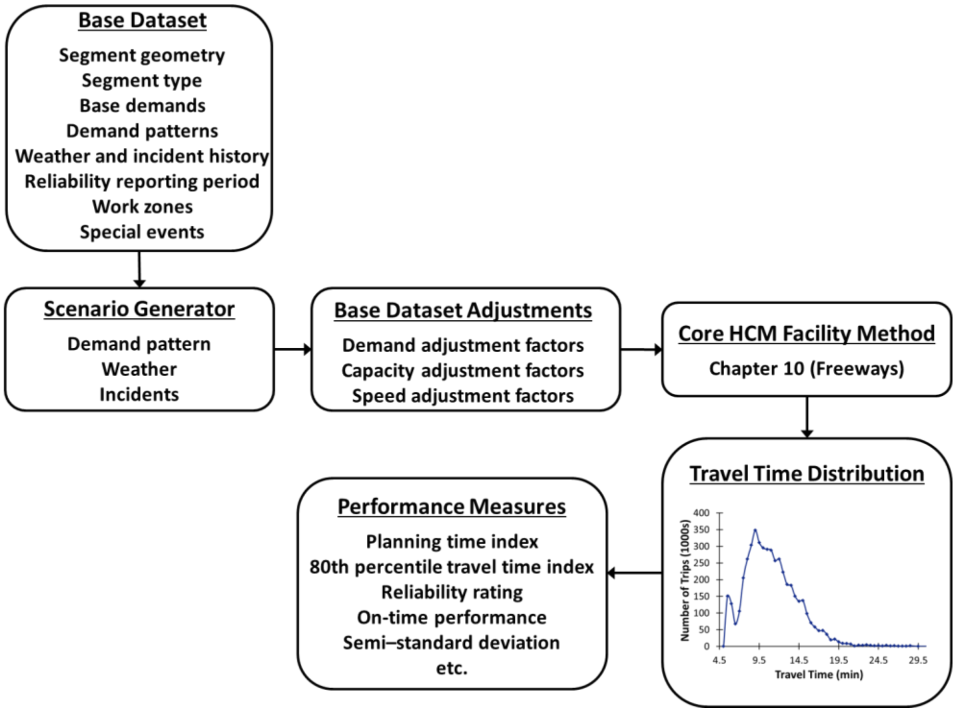
The freeway methodology is computationally intense and requires software to implement. The intensity stems from the need to create and process the input and output data associated with the hundreds to thousands of scenarios considered for a typical reliability reporting period. The objective of this section is to introduce the analyst to the calculation process and discuss the key analytic procedures. In the process, important equations, concepts, and interpretations are highlighted.

The computational details of the methodology are provided in Chapter 37, Travel Time Reliability: Supplemental. The FREEVAL-RL computational engine provided in the Technical Reference Library in the online HCM Volume 4 represents the most detailed description of the methodology.

FRAMEWORK

The freeway reliability methodology includes a base dataset, a scenario generator, and a core computational procedure inherited from Chapter 10. The computational procedure predicts travel times for each scenario, which are assembled into a travel time distribution that is used to determine performance measures of interest. These components are illustrated in Exhibit 36-13.

Exhibit 36-13
Freeway Reliability Methodology Framework



Base Dataset

The base dataset contains all the required input data for the Chapter 10 freeway facility. Some data are specific to the freeway facility being studied. They include, at a minimum, all segment geometries, free-flow speeds, lane patterns, and segment types, along with base demands that are typically, but not necessarily, reflective of average (AADT) conditions. In addition, the base dataset contains the required input data to execute this chapter's reliability methodology. These data include demand patterns, a demand multiplier, weather data, and incident data. The majority of the reliability-specific input data can be defaulted when they are not available locally, but the analyst is encouraged to supply facility-specific data whenever they are available. The Required Input Data subsection of Section 1, Introduction, describes all of the freeway-related data required for a reliability analysis. The Data Acquisition subsection of Section 2, Concepts, describes potential sources for these data.

Scenario Generation

The scenario generator develops a sufficiently complete set of scenarios that a freeway facility may experience during the reliability reporting period, along with their associated probabilities. "Sufficiently complete" means that the analyst may specify minimum threshold probabilities for including a scenario in the analysis. In addition, scenarios that produce similar inputs (e.g., demand volumes on Tuesdays, Wednesdays, and Thursdays) may be combined by the analyst. These steps can reduce the number of scenarios that are evaluated—and thus reduce analysis time—without significantly affecting the final results.

Each scenario represents a single study period (typically several hours long) that is fully characterized in terms of demand and capacity variations in time and space. The data supplied to the scenario generator are expressed as multiplicative factors that are applied to the base demand and capacity.

The scenario generation process includes the following steps:

- Adjusting the base demand to reflect day-of-week and month-of-year variations associated with a given scenario;
- Generating severe weather events on the basis of their probability of occurrence in a given time of year and adjusting capacities and free-flow speeds to reflect the effects of the weather events;
- Generating various types of incidents on the basis of their probability of occurrence and adjusting capacities to reflect their effects; and
- Incorporating user-supplied information about when and where work zones and special events occur, along with any corresponding changes to the base demand or geometry.

The results from these steps are used to develop one input dataset to the Chapter 10 procedure (incorporating multiple analysis periods) for each study period in the reliability reporting period.

Facility Evaluation

In the facility evaluation step, each scenario is provided to the core HCM freeway facility methodology for analysis. The performance measures of interest to the evaluation—in particular, travel time—are calculated for each scenario and stored. At the end of this process, a travel time distribution can be formed from the travel time results stored for each scenario.

Performance Summary

In the final step, travel time reliability is described for the entire reliability reporting period with various performance measures. The travel time distribution is used to quantify a range of variability and reliability metrics.

SCENARIO GENERATION

Traffic Demand Variation Generation

The freeway reliability methodology accounts for demand variability by adjusting the traffic demands for the analysis periods included in the base study period by the following:

1. A *demand ratio,* the average demand for a given day and month (e.g., Fridays in May) relative to the average demand for a specified day and month (e.g., AADT, Mondays in January); and
2. A *demand* multiplier, the base period demand divided by the demand for the specified day and month used in the denominator of the demand ratio.

For example, if base period demands are expressed as AADT and average daily traffic (ADT) volumes for Fridays in May are 21% higher than AADT, the demand ratio for an analysis period on a Friday in May would be 1.21. The demand multiplier would be 1.00, since both the base period demand and the demand ratio denominator are expressed as AADT. The base period demands would be divided by the demand multiplier (1.00) and multiplied by the demand ratio (1.21) to obtain the analysis period demand for a Friday in May.

If base period demands were measured on a Thursday in August, the supplied demand ratios are relative to Mondays in January, and average demands on Thursdays in August are 32% higher than average demands on Mondays in January, the demand multiplier would be 1.32. Similarly, if average demands for Fridays in May are 39% higher than for Mondays in January, the demand ratio for an analysis period on a Friday in May would be 1.39. The base period demands would be divided by the demand multiplier (1.32) and multiplied by the demand ratio (1.39) to obtain analysis period demands for Fridays in May that are 5% higher than the supplied base period demands.

Demand is varied by day of week and month of year for a maximum of 7 × 12 or 84 demand patterns that can be specified for a given year. The method assumes that variability across analysis periods is consistent throughout the study period. That is, the demand ratios are applied consistently to all of the 15-min analyis periods making up a given scenario's study period. (To continue the first example from above, the volumes associated with all analysis periods on Fridays in May would be multiplied by 1.21 from their base values.)

If demand does not vary significantly between certain days or certain months, the analyst may choose to combine days or months to reduce the total number of scenarios that will be generated and calculated (and thus reduce the analysis time). For example, local conditions permitting, the five weekdays could be consolidated into three weekday types (Monday, Tuesday to Thursday, and Friday) and the 12 months consolidated into four seasons, resulting in 3 × 4 or 12 demand patterns. When days and months are consolidated, the corresponding demand ratios are also consolidated by using average values weighted by the number of specified weekdays in each month.

The ratio of highest to lowest demand ratios for urban freeways is 1.82, on the basis of national data shown in Exhibit 36-14 (*7*), indicating a strong calendar effect on demand. The analyst may use the default national data, but it is recommended for best results that the analyst supply a 7 × 12 matrix of local demand ratios for each combination of day of week and month of year.

Demand variation due to work zones or special events must be entered directly by the analyst, as described later in this section.

Exhibit 36-14
Demand Ratios for Urban Freeways (ADT/Mondays in January)

	Day of Week						
Month	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
January	1.00	1.00	1.02	1.05	1.17	1.01	0.89
February	1.03	1.03	1.05	1.08	1.21	1.04	0.92
March	1.12	1.12	1.14	1.18	1.31	1.13	0.99
April	1.19	1.19	1.21	1.25	1.39	1.20	1.05
May	1.18	1.18	1.21	1.24	1.39	1.20	1.05
June	1.24	1.24	1.27	1.31	1.46	1.26	1.10
July	1.38	1.38	1.41	1.45	1.62	1.39	1.22
August	1.26	1.26	1.28	1.32	1.47	1.27	1.12
September	1.29	1.29	1.32	1.36	1.52	1.31	1.15
October	1.21	1.21	1.24	1.27	1.42	1.22	1.07
November	1.21	1.21	1.24	1.27	1.42	1.22	1.07
December	1.19	1.19	1.21	1.25	1.40	1.20	1.06

Source: Cambridge Systematics et al. (*7*).

Weather Event Generation

Weather events are generated on the basis of their probability of occurrence during a given month (or set of months, if months were aggregated during the traffic demand variability process). As shown in Exhibit 36-4, the method incorporates 10 categories of severe weather events that have been shown to reduce capacity by at least 4%, along with a "non–severe weather" category that encompasses all other weather conditions and that generates no capacity or speed adjustment.

Exhibit 36-15 shows the capacity adjustment factor (CAF) and free-flow speed adjustment factor (SAF) associated with each weather event (*1*) for a free-flow speed of 70 mi/h. The weather events are defined in Exhibit 36-4, which in turn is based on Exhibit 10-15 in Chapter 10, Freeway Facilities. Note that the SAF is a function of the free-flow speed; SAF values for other free-flow speeds are provided in the Default Values subsection of Section 5, Applications.

Exhibit 36-15
Weather Effects on Capacity and Speed (70-mi/h Free-Flow Speed)

Weather Event	CAF	SAF
Medium rain	0.93	0.93
Heavy rain	0.86	0.92
Light snow	0.96	0.87
Light–medium snow	0.91	0.86
Medium–heavy snow	0.89	0.84
Heavy snow	0.78	0.83
Severe cold	0.92	0.93
Low visibility	0.90	0.94
Very low visibility	0.88	0.92
Minimal visibility	0.90	0.92
Non–severe weather	1.00	1.00

Source: Vandehey et al. (*1*).
Notes: CAF = capacity adjustment factor, SAF = free-flow speed adjustment factor.

As described in the Required Input Data subsection of Section 1, Introduction, the analyst may use default weather data from any of 101 U.S. metropolitan areas, based on 2001–2010 weather records. Alternatively, the analyst may supply a 12-month by 11-weather-event matrix (132 total values) of local probabilities of each weather event, along with average durations (in minutes) for each severe event (10 total values).

Weather events are assumed to occur either at the start or in the middle of the study period, with equal probability, which results in a maximum of 11 weather events × 2 start times, or 22 weather patterns. All the segments on the facility are assumed to be affected by the weather event at the same time.

Traffic Incident Generation

Note that incident duration is defined as the length of time that the shoulder or one or more lanes are blocked. This may be different from the time to clear the incident. Incident severity reflects the maximum number of lanes blocked.

Incidents are generated on the basis of their probability of occurrence in a given month. As described in the Required Input Data subsection, the analyst may use default incident probabilities, may supply a facility-specific incident or crash rate, or may supply a 12-month by 6-incident-category matrix (72 total values) of local probabilities of each incident type, along with three possible durations (in minutes) of each incident type (18 total values). (The default duration values assume 25th, 50th, and 75th percentile durations, based on national data.)

The method makes the following assumptions about a given incident:

- The incident start time occurs either at the start or in the middle of the study period, with equal probability.
- One of the three possible incident durations for a given incident type is selected, with equal probability.
- The incident location is the first segment, middle segment, or last segment of the facility, with equal probability.

Thus there are a maximum of 2 start times × 3 durations × 3 locations × 5 incident severities = 90 patterns with an incident. There is also one "no incident" pattern. The result is a total of 91 possible incident patterns.

Exhibit 36-16 shows the CAFs associated with each incident type, derived from Exhibit 10-17 in Chapter 10. The values shown in the exhibit reflect the *remaining capacity per open lane*. For example, a two-lane closure incident on a six-lane directional facility results in a loss of two full lane capacities, in addition to maintaining only 75% of the remaining four open lanes' capacities. The result is that only three lanes worth (50%) of the facility's original six-lane capacity is maintained, consistent with Exhibit 10-17. No information is available about the effect of incidents on free-flow speed, so this effect is not modeled. As explained in the Incident Data subsection of Section 1, Introduction, full-facility closures are not modeled.

Exhibit 36-16
Incident Effects on Capacity

Directional Lanes	No Incident	Shoulder Closed	1 Lane Closed	2 Lanes Closed	3 Lanes Closed	4 Lanes Closed
2	1.00	0.81	0.70	N/A	N/A	N/A
3	1.00	0.83	0.74	0.51	N/A	N/A
4	1.00	0.85	0.77	0.50	0.52	N/A
5	1.00	0.87	0.81	0.67	0.50	0.50
6	1.00	0.89	0.85	0.75	0.52	0.52
7	1.00	0.91	0.88	0.80	0.63	0.63
8	1.00	0.93	0.89	0.84	0.66	0.66

Notes: Values represent remaining capacity per open lane, accounting for both any closed lanes and the loss of capacity in the lanes remaining open.
N/A = not applicable: the method does not permit full-facility closures.

Work Zones and Special Events

Only significant, scheduled work zones and special events are considered in the scenario generator. The analyst provides the work zone or special event schedule and characteristics (e.g., shoulder work, single lane closure). In addition, if significant changes in traffic demand are anticipated during the work zone or special event, the appropriate demand values must be provided. Capacity effects of work zones are taken primarily from the literature, including the HCM. Exhibit 36-17 shows example CAFs computed from Exhibit 10-14. Exhibit 36-17 assumes a work zone free-flow speed of 55 mi/h, which corresponds to a base capacity of 2,250 pc/h/ln. The values in the exhibit correspond to the *per lane* CAF for the open lanes. Capacity effects of special events must be entered by the analyst, since they are highly facility- and event-specific.

Exhibit 36-17
Example Work Zone Effects on Capacity for Lane Closure Scenarios

Directional Lanes	1 Lane Closed	2 Lanes Closed	3 Lanes Closed
2	0.62	N/A	N/A
3	0.64	0.64	N/A
4	0.67	0.64	0.60

Source: Computed from Exhibit 10-14; a work zone free-flow speed of 55 mi/h is assumed.
Notes: Values represent remaining capacity per open lane, accounting for both any closed lanes and the loss of capacity in the lanes remaining open.
N/A = not applicable: the method does not permit full-facility closures.

Scenario Dataset Generation

The scenario generator assumes that recurring and all nonrecurring congestion events are independent of each other. There are few empirical data to support the development of predictive models of (for example) incident types by weather condition or incidents and work zones. Therefore, the probability of a combination of two events is assumed to be equal to the product of their individual probabilities.

The total number of scenarios that will emerge cannot be predicted a priori since only a subset of combinations of demand and capacity variations due to the nonrecurring events will occur. An upper bound on the number of scenarios can be estimated, however. If the presence of work zones and special events is neglected and 12 demand pattern scenarios, 22 weather scenarios, and 91 incident scenarios are assumed, up to 24,000 scenarios can be generated for a facility. In reality, many of the combinations do not exist or are negligible (e.g., snow in the summer in most places), and the actual number of scenarios generated is a fraction of this upper bound. The scenario generator computes the fractional number of study periods each scenario is applicable to and divides that number by the number of study periods contained within the reliability reporting period to estimate each scenario's probability.

Exhibit 36-18 shows examples of scenario allocations developed by the scenario generator for a specific set of input values. The attributes listed in the exhibit provide a full specification of a given scenario.

Exhibit 36-18
Example Scenario Attributes Developed by the Scenario Generator

			Weather		Incident					
Scenario Number	**Demand Pattern**	**Scenario Probability**	**Event Type**	**Start Time**	**Type**	**Duration**	**Start Time**	**Segment**	**Incident Duration**	**Weather Duration**
1	7	0.6346%	Normal	N/A	None	N/A	N/A	N/A	N/A	N/A
10	7	0.3872%	Normal	N/A	Shoulder closed	Average	Mid SP	First	N/A	N/A
100	4	0.2640%	Medium rain	Mid SP	None	N/A	N/A	N/A	N/A	45 min
621	10	0.0360%	Medium rain	Start SP	Shoulder closed	Long	Start SP	Last	45 min	45 min
2269	4	0.00025%	Light snow	Mid SP	3 lanes closed	Short	Mid SP	Mid	60 min	135 min

Notes: N/A = not applicable; SP = study period.

FACILITY EVALUATION

Evaluation Process

Each scenario produced by the scenario generator is analyzed by using the Chapter 10 freeway facility methodology. Variations in input and output values between scenarios are effectively due to three types of adjustments:

- Demand adjustments by day of week and month of year (or aggregations of these time periods), expressed in terms of demand ratios and multipliers that are applied to the analysis period demands specified for the base scenario. Demand adjustments may also be directly specified by the analyst for work zones and special events.
- Capacity adjustments due to weather, incidents, work zones, and special events. They are expressed in terms of capacity losses due to lane closures, CAFs applied to specific segments because of incidents or work zones, and CAFs applied to the entire facility because of severe weather events. Capacity adjustments may also be directly specified by the analyst for special events.
- Free-flow speed variability due to weather conditions. This is expressed in terms of SAFs applied facilitywide for the duration of the weather event.

The Chapter 10 methodology produces a variety of performance measures, which are stored separately for each analysis period for each scenario. Each 15-min analysis period provides a building block for developing the travel time distribution.

Freeway Facilities Methodological Enhancements

This section summarizes enhancements to the HCM 2010 freeway facilities method presented in Chapter 10 that have been implemented to make the method "reliability-ready." Details of these enhancements are provided in Chapter 37, Travel Time Reliability: Supplemental.

Concurrent SAF and CAF Implementation on HCM Segments

To remain in general compliance with the HCM 2010 freeway facilities methodology, the speed prediction model (Equation 25-1) is revised. For basic segments, the new model replaces the base free-flow speed with an adjusted free-flow speed incorporating the appropriate SAF for the prevailing weather conditions.

$$S = (FFS \times SAF) + \left[1 - e^{\ln\left((FFS \times SAF) + 1 - \frac{C * CAF}{45}\right) \times \frac{v_p}{C \times CAF}}\right]$$

Equation 36-6

where

S = segment speed (mi/h),

FFS = segment free-flow speed (mi/h),

SAF = speed adjustment factor,

C = original segment capacity (pc/h/ln),

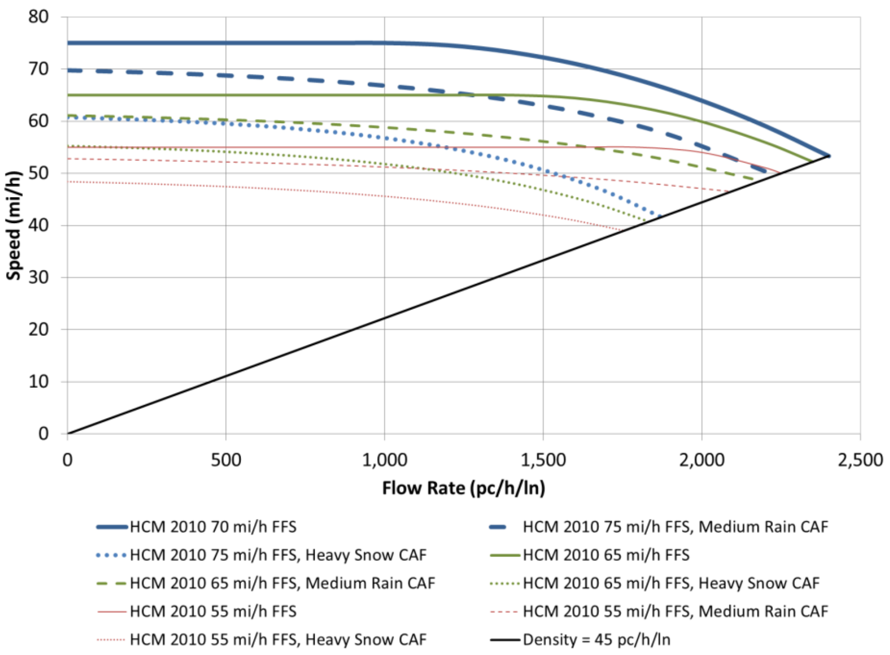
CAF = capacity adjustment factor, and

v_p = segment flow rate (pc/h/ln).

Examples of the effect of SAF and CAF on the base speed–flow relationship are shown in Exhibit 36-19. The solid lines represent the base HCM curves, while the dashed and dotted lines are revised curves resulting from speed or capacity adjustments, or both. The estimated speed from Equation 36-6 can never drop below the speed at the adjusted capacity (at a density of 45 pc/mi/ln). This constraint guarantees that the predicted speed will always be at least 1 mi/h above the estimated speed at capacity.

For ramp and weaving segments, the adjustments to capacity and speeds are made independently, since speed estimation for these segment types is independent of capacity. In other words, the CAF is applied to reducing the segment capacity (thus invoking the oversaturated regime earlier than usual), and SAF is applied to reducing the free-flow speed and, by extension, the estimated segment speed. Whenever the Chapter 12 or Chapter 13 methodology uses capacity or free-flow speed, the freeway reliability methodology replaces it with (capacity × CAF) or (free-flow speed × SAF), respectively.

Exhibit 36-19
Example Speed–Flow Curves for Basic Freeway Segments After CAF and SAF Adjustments



Notes: FFS = free-flow speed; CAF = capacity adjustment factor.

Queue Discharge Flow Rate

To model queue propagation and dissipation on congested freeway facilities more realistically, the freeway reliability methodology allows the analyst to specify a capacity loss due to freeway breakdown. This factor does not exist in the original HCM 2010 method but has been found to affect the duration and severity of congestion significantly. The capacity loss averages 7% during breakdown (*12*). Queue discharge flow rates are applied as soon as a queue develops and remain in effect until the queue has fully dissipated.

Additional Performance Measures

Some scenario runs are likely to generate severe congestion when a combination of high demand, severe weather, and incidents occurs. Some cases (e.g., multiple interacting bottlenecks) may be beyond the ability of a macroscopic model to analyze. Besides providing warning flags for such occurrences, the method incorporates additional performance measures to monitor those effects:

- Total number of vehicles denied entry onto the facility when the first segment is fully queued and
- Denied-entry-vehicle queue length upstream of Segment 1 in each analysis period.

The method also incorporates new reliability measures to enable before-and-after comparisons. These measures include the following:

- *Segment TTI,* the average segment travel time in an analysis period divided by its corresponding free-flow travel time. Segment TTI is calculated and reported for each segment in each analysis period.

- *Facility TTI*, based on a weighted average of the probabilities associated with each TTI observation. Each 15-min analysis period contributes one data point to the overall facility travel time distribution. Each facility TTI observation occurs with a probability associated with its scenario. For example, if a study period scenario has a 2.4% probability associated with a 2-h study period (eight analysis periods), then each analysis period occurs with a probability of 2.4% / 8 = 0.3%.

PERFORMANCE SUMMARY

In this step, the stored travel time distribution is summarized for the entire reliability reporting period by using various performance measures:

See Section 2, Concepts, for definitions of these measures.

- Mean TTI,
- PTI,
- Reliability rating,
- 80th percentile TTI,
- Semi–standard deviation,
- Standard deviation,
- Failure or on-time percentage based on a target speed,
- Policy index based on a target speed, and
- Misery index.

4. URBAN STREET METHODOLOGY

OVERVIEW

This section describes the methodology for evaluating the reliability of an urban street facility. It also describes the extensions to the base HCM urban street facility method (Chapter 16) that are required for computing reliability performance measures.

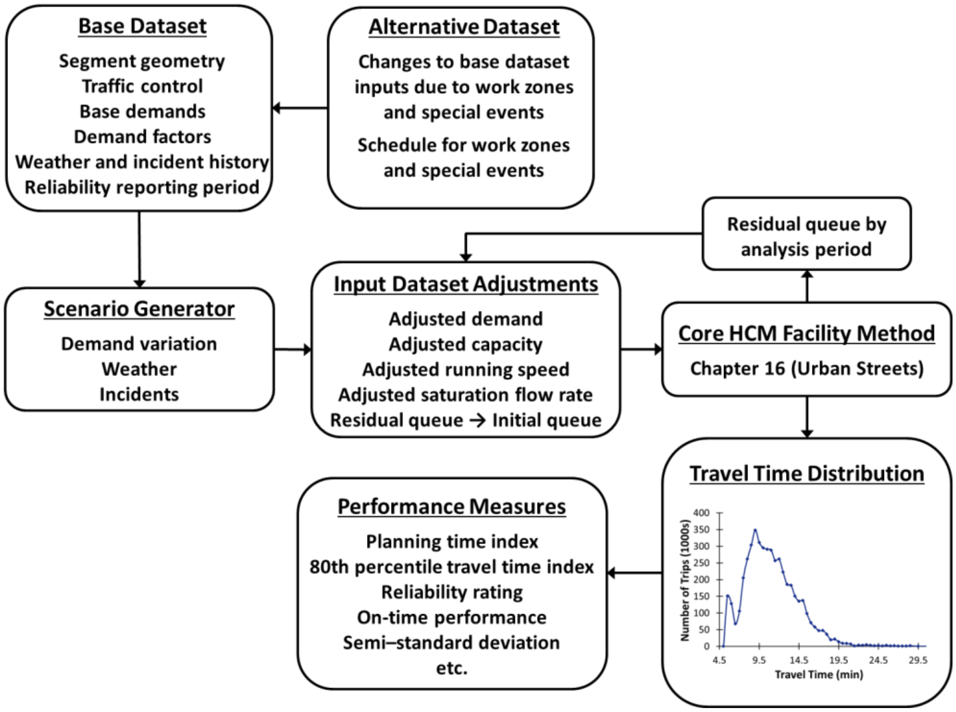
The urban street reliability methodology is computationally intense and requires software to implement. The intensity stems from the need to create and process the input and output data associated with the hundreds or thousands of scenarios considered for a typical reliability reporting period. The objective of this section is to introduce the analyst to the calculation process and discuss the key analytic procedures. Important equations, concepts, and interpretations are highlighted.

The computational details of the methodology are provided in Chapter 37, Travel Time Reliability: Supplemental. The STREETVAL computational engine provided in the Technical Reference Library in the online HCM Volume 4 represents the most detailed description of the methodology.

FRAMEWORK

The sequence of calculations in the reliability methodology is shown in Exhibit 36-20. There are five main steps: (*a*) establishing base and alternative datasets, (*b*) generating scenarios, (*c*) evaluating each scenario with the Chapter 16 operational method, (*d*) compiling travel times for each analysis period in the reliability reporting period, and (*e*) producing reliability performance measures.

Exhibit 36-20
Urban Street Reliability Methodology Framework



Data Depository

Every urban street reliability analysis requires a *base dataset.* This dataset describes the traffic demand, geometry, and signal timing conditions for the intersections and segments along the facility during the study period, when no work zones are present and no special events occur.

Additional datasets are used, as needed, to describe the conditions when a specific work zone is present or when a special event occurs. These datasets are called the *alternative datasets.* One alternative dataset is used for each time period during the reliability reporting period when a specific work zone is present, a specific special event occurs, or a unique combination of these conditions occurs during the study period.

The Required Input Data subsection of Section 1, Introduction, describes all the urban street–related data required for a reliability analysis. The Data Acquisition subsection of Section 2, Concepts, describes potential sources for these data.

Scenario Generation

The scenario generation stage consists of four sequential procedures: (*a*) weather event generation, (*b*) traffic demand variation generation, (*c*) traffic incident generation, and (*d*) scenario dataset generation. Each procedure processes in chronological order the set of analysis periods that make up the reliability reporting period. This section gives an overview of the scenario generation process; a detailed description is provided in Chapter 37, Travel Time Reliability: Supplemental.

Weather Event Generation

The weather event procedure generates rain and snow events during the reliability reporting period. The dates, times, types (i.e., rain or snow), and durations of severe weather events are generated. These data are used to adjust the saturation flow rate and speed of facility traffic for each analysis period. The procedure also predicts the time after each weather event that the pavement remains wet or covered by snow or ice, since the presence of these conditions influences running speed and intersection saturation flow rate.

Future research may indicate that additional weather types affect arterial operation. At this time, available research supports assessment of rain and snow events on arterial operation.

Traffic Demand Variation Generation

The traffic demand variation procedure identifies the appropriate traffic demand adjustment factors for each analysis period in the reliability reporting period. A set of factors accounts for systematic demand variation by hour of day, day of week, and month of year. Default values for these factors are provided in Section 5, Applications; however, local values are recommended when available.

Traffic Incident Generation

The traffic incident procedure generates incident dates, times, and durations. It also determines incident types (i.e., crash or noncrash), severity levels, and locations on the facility. Location is defined by the intersection or segment on which the incident occurs and whether the incident occurs on the shoulder, in one lane, or in multiple lanes. The procedure incorporates weather and traffic demand variation information from the previous procedures in generating incidents.

Scenario Dataset Generation

The scenario dataset generation procedure uses the results from the preceding procedures to develop one HCM dataset for each analysis period in the reliability reporting period. Each analysis period is considered to be one scenario. The base dataset is modified to reflect conditions present during a given analysis period. Traffic volumes are modified at each intersection and driveway. Saturation flow rates are adjusted at intersections influenced by an incident or a weather event, and speeds are adjusted for segments influenced by an incident or a weather event. Dates and times represent a common basis for tracking events and conditions from one analysis period to the next.

Facility Evaluation

As shown in Exhibit 36-20, the facility evaluation stage consists of two tasks that are repeated in sequence for each analysis period. The analysis periods are evaluated in chronological order.

First, the dataset associated with a given analysis period is evaluated by using the urban street facility (Chapter 16) method. The performance measures output by the method are archived.

Second, the dataset associated with the next analysis period is modified, if necessary, on the basis of the results of the current analysis period. Specifically, the initial queue input value for the next analysis period is set equal to the residual queue output for the current analysis period.

Performance Summary

The performance summary stage consists of two sequential tasks. First, the analyst identifies a specific direction of travel and the performance measures of interest. The desired performance measures are extracted from the facility evaluation archive for each analysis period in the reliability reporting period. Available measures, as defined in Chapter 17, Urban Street Segments, are as follows:

- Travel time,
- Travel speed,
- Stop rate,
- Running time, and
- Through delay.

The analyst also indicates whether the performance measures of interest should be representative of the entire facility or a specific segment. The first three measures in the above list are available for facility evaluation. All five measures are available for segment evaluation. At the conclusion of this task, the collected data represent observations of the performance measures for each analysis period occurring during the reliability reporting period (or a sampled subset thereof).

Next, the selected performance measure data are summarized by using the following statistics:

- Average;
- Standard deviation;
- Skewness;
- Median;
- 10th, 80th, 85th, and 95th percentiles; and
- Number of observations.

In addition, the average base free-flow speed is always reported. It can be used with one or more of the distribution statistics to compute various variability and reliability measures, such as the TTI and the reliability rating.

ANALYSIS TECHNIQUES

Work Zones and Special Events

Work zones and special events influence traffic demand levels and travel patterns. To minimize the impact of work zones and special events on traffic operation, agencies responsible for managing traffic in the vicinity of a work zone or special event often reallocate some traffic lanes or alter the signal operation to increase the capacity of specific traffic movements. These characteristics mean that the effect of each work zone and special event on facility performance is unique. Multiple work zones and special events can occur during the reliability reporting period.

The reliability methodology incorporates work zone and special event influences in the evaluation results. However, the analyst must describe each work zone and special event by using an alternative dataset. Each dataset describes the traffic demand, geometry, and signal timing conditions when the work zone is present or the special event is under way. A start date and duration are associated with each dataset.

The presence of a work zone can have a significant effect on traffic demand levels. The extent of the effect will depend partly on the availability of alternative routes, the number of days the work zone is in operation, and the volume-to-capacity ratio of the segment or intersection approach within the work zone.

When the reliability methodology is used, the analyst must provide estimates of traffic demand volumes during the work zone or special event. The estimates should reflect the effect of diversion and can be based on field measurements, judgment, or areawide traffic planning models. They are recorded by the analyst in the corresponding alternative dataset.

The analyst must have information about lane closures, alternative lane assignments, and special signal timing that is present during the work zone or special event. The information can be based on agency policy or experience with previous work zones or events. The available lanes, lane assignments, and signal timing are recorded by the analyst in the corresponding alternative dataset.

Multiple Study Periods

The geometric design elements, traffic control features (including signal timing plans), and directional distribution of traffic are assumed to be constant during the study period. If any of these factors varies significantly during certain periods of the day (e.g., morning peak or evening peak), each unique period should be the focus of a separate reliability evaluation. In this regard, each unique period represents one study period.

When multiple study period evaluations are undertaken for a common facility, the set of analysis period averages for each evaluation can be merged to evaluate the overall reliability. In this manner, the combined data for a given performance measure represent the distribution of interest. The various reliability measures are then quantified by using this combined distribution.

Alternatives Analysis

Weather events; traffic demand; and traffic incident occurrence, type, and location have both systematic and random elements. To the extent practical, the reliability methodology accounts for the systematic variation component in its predictive models. Specifically, it recognizes temporal changes in weather and traffic demand during the year, month, and day. It recognizes the influence of geographic location on weather and the influence of weather and traffic demand on incident occurrence.

Models of the systematic influences are included in the methodology. They are used to predict average weather, demand, and incident conditions during each analysis period. However, the use of averages to describe weather events and incident occurrence for such short time periods is counter to the objectives of reliability evaluation. The random element of weather events, demand variation, and traffic incident occurrence introduces a high degree of variability in the collective set of analysis periods that make up the reliability reporting period. Thus, replication of these random elements is important in any reliability evaluation. Monte Carlo methods are used for this purpose in the urban street reliability methodology.

A Monte Carlo approach uses essentially random inputs (within realistic limits) to model a system and produce probable outcomes.

A random number seed is used with the Monte Carlo methods in the reliability methodology. A seed is used so that the sequence of random events can be reproduced. Unique seed numbers are separately established for weather events, demand variation, and incidents. For a given set of three seed numbers, a unique combination of weather events, demand levels, and incidents is estimated for each analysis period in the reliability reporting period.

One, two, or three of the seed numbers can be changed to generate a different set of conditions, if desired. For example, if the seed number for weather events is changed, a new series of weather events is created, and to the extent that weather influences incident occurrence, a new series of incidents is created. Similarly, the seed number for demand variation can be used to control whether a new series of demand levels is created. The seed number for incidents can be used to control whether a new series of incidents is created.

When alternatives are evaluated, the analyst will likely use one set of seed numbers as a variance reduction technique. In this application, the same seed numbers are used for all evaluations. With this approach, the results from an evaluation of one alternative can be compared with those from an evaluation of the baseline condition. Any observed difference in the results can be attributed to the changes associated with the alternative (i.e., they are not due to random changes in weather or incident events among the evaluations).

Confidence Intervals

A complete exploration of reliability would likely entail the use of multiple, separate evaluations of the same reliability reporting period, with each evaluation using a separate set of random number seeds. This approach may be particularly useful when the facility has infrequent weather events or incidents. With this approach, the evaluation is replicated multiple times, and the performance measures from each replication are averaged to produce a more reliable estimate of their long-run value. The confidence interval (expressed as a range) for the average produced in this manner can be computed with the following equation.

$$CI_{1-\alpha} = 2 \times t_{(1-\alpha/2),N-1} \times \frac{s}{\sqrt{N}}$$

Equation 36-7

where

$CI_{1-\alpha}$ = confidence interval for the true average value, with a level of confidence of $1 - \alpha$;

$t_{(1-\alpha),N-1}$ = Student's t-statistic for the probability of a two-sided error of α, with $N - 1$ degrees of freedom;

N = number of replications; and

s = standard deviation of the subject performance measure, computed by using results from the N replications.

The variable α equals the probability that the true average value lies outside of the confidence interval. Values selected for α typically range from 0.05 (desirable) to 0.10. Selected values of Student's t-statistic are provided in Exhibit 36-21.

Exhibit 36-21
Student's *t*-Statistic

	Student's *t*-Statistic for Two Values of α	
Number of Replications	**α = 0.05**	**α = 0.10**
3	4.30	2.92
4	3.18	2.35
5	2.78	2.13
10	2.26	1.83
15	2.14	1.76
30	2.05	1.70

5. APPLICATIONS

DEFAULT VALUES

This section provides default values for much of the input data used by this chapter's reliability methodologies. Agencies are encouraged, when possible, to develop local default values based on field measurements of facilities in their jurisdiction. Local defaults provide a better means of ensuring accuracy in analysis results. Facility-specific values provide the best means. In the absence of local data, this section's default values can be used when the analyst believes that the values are reasonable for the facility to which they are applied.

Freeways

Traffic Demand Variability

Exhibit 36-22 and Exhibit 36-23 present default demand ratios by day of week and month of year for urban and rural freeway facilities, respectively. The ratios were derived from a national freeway dataset developed by SHRP 2 Project L03 (*7*). All ratios reflect demand relative to a Monday in January. Where possible, analysts should obtain local or regional estimates of demand variability to account for facility-specific and seasonal trends on the subject facility.

Exhibit 36-22
Default Urban Freeway Demand Ratios (ADT/Mondays in January)

	Day of Week						
Month	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
January	1.00	1.00	1.02	1.05	1.17	1.01	0.89
February	1.03	1.03	1.05	1.08	1.21	1.04	0.92
March	1.12	1.12	1.14	1.18	1.31	1.13	0.99
April	1.19	1.19	1.21	1.25	1.39	1.20	1.05
May	1.18	1.18	1.21	1.24	1.39	1.20	1.05
June	1.24	1.24	1.27	1.31	1.46	1.26	1.10
July	1.38	1.38	1.41	1.45	1.62	1.39	1.22
August	1.26	1.26	1.28	1.32	1.47	1.27	1.12
September	1.29	1.29	1.32	1.36	1.52	1.31	1.15
October	1.21	1.21	1.24	1.27	1.42	1.22	1.07
November	1.21	1.21	1.24	1.27	1.42	1.22	1.07
December	1.19	1.19	1.21	1.25	1.40	1.20	1.06

Source: Derived from data presented by Cambridge Systematics et al. (*7*).
Note: Ratios represent demand relative to a Monday in January.

Exhibit 36-23
Default Rural Freeway Demand Ratios (ADT/Mondays in January)

	Day of Week						
Month	**Monday**	**Tuesday**	**Wednesday**	**Thursday**	**Friday**	**Saturday**	**Sunday**
January	1.00	0.96	0.98	1.03	1.22	1.11	1.06
February	1.11	1.06	1.09	1.14	1.35	1.23	1.18
March	1.24	1.19	1.21	1.28	1.51	1.37	1.32
April	1.33	1.27	1.30	1.37	1.62	1.47	1.41
May	1.46	1.39	1.42	1.50	1.78	1.61	1.55
June	1.48	1.42	1.45	1.53	1.81	1.63	1.57
July	1.66	1.59	1.63	1.72	2.03	1.84	1.77
August	1.52	1.46	1.49	1.57	1.86	1.68	1.62
September	1.46	1.39	1.42	1.50	1.78	1.61	1.55
October	1.33	1.28	1.31	1.38	1.63	1.47	1.42
November	1.30	1.25	1.28	1.35	1.59	1.44	1.39
December	1.17	1.12	1.14	1.20	1.43	1.29	1.24

Source: Derived from data presented by Cambridge Systematics et al. (*7*).
Note: Ratios represent demand relative to a Monday in January.

Weather Events

Weather event probabilities by month of each weather event for 101 U.S. metropolitan areas are provided in the (ordinarily hidden) "Weather_DB" tab of the FREEVAL-RL spreadsheet, available in the online HCM Volume 4. Average durations, in hours, of each weather event for the same metropolitan areas are provided in the (ordinarily hidden) "W_DUR" spreadsheet tab.

Incident Probabilities and Durations

Exhibit 36-24 provides mean distributions of freeway incidents by severity. Exhibit 36-25 provides default incident durations by incident type.

Exhibit 36-24
Default Freeway Incident Severity Distributions

Incident Type			
Shoulder Closed	**1 Lane Closed**	**2 Lanes Closed**	**3+ Lanes Closed**
75.4%	19.6%	3.1%	1.9%

Source: Vandehey et al. (*1*).

Exhibit 36-25
Default Freeway Incident Durations (min)

	Incident Type				
Month	**Shoulder Closed**	**1 Lane Closed**	**2 Lanes Closed**	**3 Lanes Closed**	**4 Lanes Closed**
25th percentile	17	20	39	47	47
50th percentile	32	34	53	69	69
75th percentile	47	48	67	91	91

Source: Vandehey et al. (*1*).

Capacity Adjustment Factors and Speed Adjustment Factors

Exhibit 36-26 provides default CAFs and SAFs by weather type and facility free-flow speed. Note that changes in CAFs and SAFs related to decreasing visibility in the exhibit may be counterintuitive since they are based on a single site (see Exhibit 10-15 in Chapter 10).

Exhibit 36-26
Default CAFs and SAFs by Weather Condition

	Capacity Adjustment Factors					Speed Adjustment Factors				
Weather Type	**55 mi/h**	**60 mi/h**	**65 mi/h**	**70 mi/h**	**75 mi/h**	**55 mi/h**	**60 mi/h**	**65 mi/h**	**70 mi/h**	**75 mi/h**
Medium rain	0.94	0.93	0.92	0.91	0.90	0.96	0.95	0.94	0.93	0.93
Heavy rain	0.89	0.88	0.86	0.84	0.82	0.94	0.93	0.93	0.92	0.91
Light snow	0.97	0.96	0.96	0.95	0.95	0.94	0.92	0.89	0.87	0.84
Light–medium snow	0.95	0.94	0.92	0.90	0.88	0.92	0.90	0.88	0.86	0.83
Medium–heavy snow	0.93	0.91	0.90	0.88	0.87	0.90	0.88	0.86	0.84	0.82
Heavy snow	0.80	0.78	0.76	0.74	0.72	0.88	0.86	0.85	0.83	0.81
Severe cold	0.93	0.92	0.92	0.91	0.90	0.95	0.95	0.94	0.93	0.92
Low visibility	0.90	0.90	0.90	0.90	0.90	0.96	0.95	0.94	0.94	0.93
Very low visibility	0.88	0.88	0.88	0.88	0.88	0.95	0.94	0.93	0.92	0.91
Minimal visibility	0.90	0.90	0.90	0.90	0.90	0.95	0.94	0.93	0.92	0.91
Non–severe weather	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00

Notes: Speeds given in column heads are free-flow speeds.
Weather types are defined in Exhibit 36-4.

Urban Streets

The urban street default values have been derived from the best available research and data at the time of writing. Some of these values are based on the findings of research projects, and others are based on an aggregation of data from agency databases. In contrast, some default values have a less substantial basis. In some instances, the values are based partly on experience and judgment. Regardless, analysts are encouraged to update the default values whenever possible by using data representative of local conditions. It is recognized that, in some jurisdictions, updates to the incident-related default values may not be possible until transportation agencies maintain more detailed urban street incident records.

Traffic Demand Variability

Default hour-of-day, day-of-week, and month-of-year traffic demand adjustment factors are given in Exhibit 36-27 through Exhibit 36-29, respectively. The factors should be replaced with data from permanent traffic count stations whenever available for streets that are similar to the subject facility and located near it. The functional classes were defined in the Required Input Data section.

Exhibit 36-27
Default Urban Street Hour-of-Day Demand Ratios (ADT/AADT)

Hour Starting	Expressway		Principal Arterial		Minor Arterial	
	Weekday	Weekend	Weekday	Weekend	Weekday	Weekend
Midnight	0.010	0.023	0.010	0.023	0.010	0.028
1 a.m.	0.006	0.015	0.006	0.014	0.006	0.023
2 a.m.	0.004	0.008	0.005	0.010	0.004	0.021
3 a.m.	0.004	0.005	0.005	0.006	0.002	0.008
4 a.m.	0.007	0.005	0.009	0.006	0.002	0.005
5 a.m.	0.025	0.009	0.030	0.010	0.007	0.005
6 a.m.	0.058	0.016	0.054	0.017	0.023	0.011
7 a.m.	0.077	0.023	0.071	0.024	0.067	0.018
8 a.m.	0.053	0.036	0.058	0.035	0.066	0.030
9 a.m.	0.037	0.045	0.047	0.046	0.054	0.048
10 a.m.	0.037	0.057	0.046	0.056	0.051	0.054
11 a.m.	0.042	0.066	0.050	0.054	0.056	0.057
Noon	0.045	0.076	0.053	0.071	0.071	0.074
1 p.m.	0.045	0.073	0.054	0.071	0.066	0.071
2 p.m.	0.057	0.074	0.063	0.072	0.060	0.069
3 p.m.	0.073	0.075	0.069	0.073	0.062	0.067
4 p.m.	0.087	0.075	0.072	0.073	0.063	0.071
5 p.m.	0.090	0.071	0.077	0.073	0.075	0.068
6 p.m.	0.068	0.063	0.062	0.063	0.070	0.067
7 p.m.	0.049	0.051	0.044	0.052	0.053	0.056
8 p.m.	0.040	0.043	0.035	0.044	0.044	0.049
9 p.m.	0.037	0.037	0.033	0.038	0.035	0.040
10 p.m.	0.029	0.032	0.026	0.033	0.033	0.035
11 p.m.	0.019	0.023	0.021	0.026	0.019	0.024

Source: Hallenbeck et al. (*13*).

Exhibit 36-28
Default Urban Street Day-of-Week Demand Ratios (ADT/AADT)

Day	Demand Ratio
Sunday	0.87
Monday	0.98
Tuesday	0.98
Wednesday	1.00
Thursday	1.03
Friday	1.15
Saturday	0.99

Source: Hallenbeck et al. (*13*).

Exhibit 36-29
Default Urban Street Month-of-Year Demand Ratios (ADT/AADT)

Month	Expressway	Principal Arterial	Minor Arterial
January	0.802	0.831	0.881
February	0.874	1.021	0.944
March	0.936	1.030	1.016
April	0.958	0.987	0.844
May	1.026	1.012	1.025
June	1.068	1.050	1.060
July	1.107	0.991	1.150
August	1.142	1.054	1.110
September	1.088	1.091	1.081
October	1.069	0.952	1.036
November	0.962	0.992	0.989
December	0.933	0.938	0.903

Source: Hallenbeck et al. (*13*).

Weather Events

Average weather statistics for 2001–2010 by month for 284 U.S. locations are provided in the STREETVAL computational engine available in the online HCM Volume 4. More recent weather data can be obtained from NCDC (*8, 9*). Exhibit 36-30 provides other weather-related default values.

Exhibit 36-30
Urban Street Weather-Related Default Values

Input Data Item	Default Value
Pavement runoff duration for snow event	0.5 h
Demand change factor for dry weather	1.00
Demand change factor for rain event	1.00
Demand change factor for snow event	0.80

The three "demand change factors" account for a change in traffic demand due to weather conditions. The demand volume is multiplied by the demand change factor corresponding to the weather associated with an analysis period. A factor less than 1.0 corresponds to a reduction in demand.

Research indicates that urban street traffic demand tends to drop 15% to 30% during snow events (*14*). These motorists likely altered the start time of their commute or stayed home to avoid the bad weather. In the absence of local data, a default value of 0.80 may be used for snow events. The research is less clear on the effect of rain on traffic demand. The effect of rain may vary with the trip purpose and the annual frequency of rain events in the vicinity of the subject facility. A default factor value of 1.0 is recommended for rain events. No adjustment to demand is made for dry weather.

Incidents

Exhibit 36-31 provides incident-related default values for urban streets.

The crash frequency adjustment factor is the ratio of hourly crash frequency during the weather event to the hourly crash rate during clear, dry hours. It is computed by using 1 or more years of historical weather data and crash data for the region in which the subject facility is located.

The adjustment factor for a specific weather condition is computed from (*a*) the number of hours for which the weather condition exists for the year and (*b*) the count of crashes during those hours. An hourly crash frequency for the weather condition fc_{wea} is computed by dividing the crash count by the number of hours. By a similar technique, the hourly crash frequency is computed for dry pavement hours fc_{dry}. The crash frequency adjustment factor for the weather condition is computed as the ratio of the two frequencies (i.e., $CFAF_{wea} = fc_{wea} / fc_{dry}$).

The crash frequency adjustment factor includes consideration of the effect of the weather event on traffic volume (i.e., volume may be reduced because of bad weather) and on crash risk (i.e., wet pavement may increase the potential for a crash). For example, if rainfall is envisioned to increase crash risk by 200% and to decrease traffic volume by 10%, the crash frequency adjustment factor for rainfall is 2.70 (= 3.0 × 0.9).

Exhibit 36-31
Urban Street Incident Default Values

Input Data Element	Default Values
Crash frequency adjustment factor for weather conditions	Rainfall: 2.0 Wet pavement (not raining): 3.0 Snowfall: 1.5 Snow or ice on pavement (not snowing): 2.75
Incident detection time	2.0 min (all weather conditions)
Incident response time	Clear, dry: 15.0 min Rainfall: 15.0 min Wet pavement (not raining): 15.0 min Snowfall: 20.4 min Snow or ice on pavement (not snowing): 20.4 min
Incident clearance time	See Exhibit 36-32
Incident distribution	See Exhibit 36-33 and Exhibit 36-34

Source: Vandehey et al. (*1*).

Incident duration is computed as the sum of the incident detection time, response time, and clearance time. The incident detection time is the time period starting with the occurrence of the incident and ending when the response officials are notified of the incident. A default value of 2.0 min is recommended for this variable.

Incident response time is the time period from the receipt of incident notification by officials to the time the first response vehicle arrives at the scene of the incident. This time will likely vary among jurisdictions and facilities, depending on the priority placed on street system management and the connectivity of the street system. A default value of 15 min is used for all weather conditions, except when snow is on the pavement. When there is snowfall or snow or ice is on the pavement, the default value is 20.4 min.

Incident clearance time is the time from the arrival of the first response vehicle to the time when the incident and service vehicles no longer directly affect travel on the roadway. This time varies by incident location, type, and severity. Default clearance times are provided in Exhibit 36-32. The default distributions for segments and intersections are the same in this exhibit. Segments and intersections are differentiated because the method allows the analyst to provide different clearance times for segments and intersections when local values are available.

The default incident type distribution time is provided in Exhibit 36-33 and Exhibit 36-34. Research indicates that this distribution varies by incident location, type, and severity. The first table provides the distribution for urban streets with shoulders. The second table provides the distribution for urban streets without shoulders. The joint proportion in the last column of each exhibit represents the product of the proportions for each of the preceding incident categories.

Exhibit 36-32
Default Urban Street Incident Clearance Times

Street Location	Event Type	Lane Location	Severity[a]	Clearance Time by Weather Condition (min) Dry	Rainfall	Wet Pavement	Snow Or Ice[b]
Segment	Crash	One lane	FI	56.4	42.1	43.5	76.7
			PDO	39.5	28.6	29.7	53.7
		2+ lanes	FI	56.4	42.1	43.5	76.7
			PDO	39.5	28.6	29.7	53.7
		Shoulder	FI	56.4	42.1	43.5	76.7
			PDO	39.5	28.6	29.7	53.7
	Non-crash	One lane	Breakdown	10.8	5.6	5.7	14.7
			Other	6.7	2.4	2.8	9.1
		2+ lanes	Breakdown	10.8	5.6	5.7	14.7
			Other	6.7	2.4	2.8	9.1
		Shoulder	Breakdown	10.8	5.6	5.7	14.7
			Other	6.7	2.4	2.8	9.1
Signalized intersection	Crash	One lane	FI	56.4	42.1	43.5	76.7
			PDO	39.5	28.6	29.7	53.7
		2+ lanes	FI	56.4	42.1	43.5	76.7
			PDO	39.5	28.6	29.7	53.7
		Shoulder	FI	56.4	42.1	43.5	76.7
			PDO	39.5	28.6	29.7	53.7
	Non-crash	One lane	Breakdown	10.8	5.6	5.7	14.7
			Other	6.7	2.4	2.8	9.1
		2+ lanes	Breakdown	10.8	5.6	5.7	14.7
			Other	6.7	2.4	2.8	9.1
		Shoulder	Breakdown	10.8	5.6	5.7	14.7
			Other	6.7	2.4	2.8	9.1

Source: Vandehey et al. (*1*).
Notes: [a] FI = fatal or injury crash; PDO = property-damage-only crash.
[b] Applies to snowfall and to snow or ice on pavement (but not snowing).

Exhibit 36-33
Default Urban Street Incident Distribution with Shoulder Presence

Street Location	Incident Type Type	Proportion	Incident Location Lanes Affected	Proportion	Incident Severity Severity[a]	Proportion	Joint Proportion
Segment	Crash	0.358	1 lane	0.335	FI	0.304	0.036
					PDO	0.696	0.083
			2+ lanes	0.163	FI	0.478	0.028
					PDO	0.522	0.030
			Shoulder	0.502	FI	0.111	0.020
					PDO	0.889	0.160
	Non-crash	0.642	1 lane	0.849	Breakdown	0.836	0.456
					Other	0.164	0.089
			2+ lanes	0.119	Breakdown	0.773	0.059
					Other	0.227	0.017
			Shoulder	0.032	Breakdown	0.667	0.014
					Other	0.333	0.007
						Total:	1.000
Signalized intersection	Crash	0.310	1 lane	0.314	FI	0.378	0.037
					PDO	0.622	0.061
			2+ lanes	0.144	FI	0.412	0.018
					PDO	0.588	0.026
			Shoulder	0.542	FI	0.109	0.018
					PDO	0.891	0.150
	Non-crash	0.690	1 lane	0.829	Breakdown	0.849	0.486
					Other	0.151	0.086
			2+ lanes	0.141	Breakdown	0.865	0.084
					Other	0.135	0.013
			Shoulder	0.030	Breakdown	0.875	0.018
					Other	0.125	0.003
						Total:	1.000

Source: Vandehey et al. (*1*).
Notes: [a] FI = fatal or injury crash; PDO = property-damage-only crash; other = not breakdown (e.g., debris).

Exhibit 36-34
Default Urban Street Incident Distribution Without Shoulder Presence

	Incident Type		Incident Location		Incident Severity		
Street Location	Type	Proportion	Lanes Affected	Proportion	Severity[a]	Proportion	Joint Proportion
Segment	Crash	0.358	1 lane	0.837	FI	0.304	0.091
					PDO	0.696	0.209
			2+ lanes	0.163	FI	0.478	0.028
					PDO	0.522	0.030
	Non-crash	0.642	1 lane	0.881	Breakdown	0.836	0.473
					Other	0.164	0.093
			2+ lanes	0.119	Breakdown	0.773	0.059
					Other	0.227	0.017
						Total:	1.000
Signalized intersection	Crash	0.310	1 lane	0.856	FI	0.378	0.100
					PDO	0.622	0.165
			2+ lanes	0.144	FI	0.412	0.018
					PDO	0.588	0.026
	Non-crash	0.690	1 lane	0.859	Breakdown	0.849	0.503
					Other	0.151	0.089
			2+ lanes	0.141	Breakdown	0.865	0.084
					Other	0.135	0.013
						Total:	1.000

Source: Vandehey et al. (*1*).
Notes: [a] FI = fatal or injury crash; PDO = property-damage-only crash; other = not breakdown (e.g., debris).

USE CASES

Travel time reliability measures can be applied to a number of planning and roadway operating agency activities, including those given in Exhibit 36-35.

Exhibit 36-35
Use Cases of Travel Time Reliability

Application	Use Cases for Travel Time Reliability
Long-range transportation plan Transportation improvement program Corridor or area plans Major investment studies Congestion management Operations planning	• Identifying *existing* facilities not meeting reliability standards. • Identifying *future* facilities not meeting reliability standards. • Generating alternatives to address reliability problems. • Evaluating reliability benefits of improvement alternatives. • Prioritizing operational improvements and traditional capacity improvements. • Evaluating the probability of achieving acceptable reliability and LOS.
Long-range planning: demand forecasting	• Modeling choice between tolled and untolled facilities. • Improving modeling of destination, time of day, mode, and route choice.

Each of these applications has several potential uses for travel time reliability. Reliability may be assessed for existing or future facilities to identify current problem spots and future deficiencies in system operation. Reliability may provide additional performance measures that can be used in generating and evaluating alternatives. Reliability may supplement conventional measurements for prioritizing improvement projects.

Planning has traditionally focused on capacity improvements and has been relatively insensitive to the reliability improvements that come with operations improvements. Thus, reliability can become an important new measure in identifying improvement alternatives, evaluating their benefits, and prioritizing them more accurately in relation to conventional capacity improvements.

Reliability adds another dimension of information on facility performance that can aid travel demand models in predicting the conditions under which people will choose to pay a toll for more reliable service. Reliability will enable better destination, time-of-day, mode, and route choice models.

Use Case No. 1: Detecting Existing Deficiencies

This use case for reliability methods in the HCM involves monitoring conditions on a facility, identifying unacceptable performance, and detecting the primary causes of unreliable facility operation. It involves selecting the appropriate study period, performance measures, and thresholds of acceptance; calibrating the HCM operations models; and expanding limited data to a full reliability dataset.

Use Case No. 2: Forecasting Problems

This use case evaluates future reliability conditions on a facility, including the following:

- Expanding average annual (daily, peak period, or peak hour) volumes (forecast demand) to the full variety of study period demands,
- Estimating facility travel times by time slice within the full study period, and
- Comparing future with existing performance and identifying "significant" changes in performance.

The following are among the forecasting questions that Case 2 addresses:

1. How to forecast weather:
    a. Use of Monte Carlo or expected value techniques to forecast the frequency of future weather events.
    b. Number of years that the forecast must be carried into the future to obtain a reasonably likely set of scenarios.
2. How to forecast incident frequency:
    a. Use of Monte Carlo or expected-value techniques.
    b. Number of future years that must be forecast to obtain a reasonably likely set of scenarios.
    c. Prediction of the effect of capacity improvements, demand changes, and active traffic and demand management (ATDM) improvements on crash frequencies.
3. Dealing with congestion overflows (e.g., over the entry link, over the last analysis period) when performance measures are computed and compared with existing conditions.
4. Calibrating this chapter's forecast reliability for future conditions to field-measured reliability under existing conditions (for data-rich agencies).

Use Case No. 3: Generating Alternatives

This use case identifies alternative operational and capacity improvements for addressing reliability problems. Selection of operational and capacity improvements that are likely to be best in addressing the primary causes of reliability problems on the facility is included.

This case requires that the analyst

1. Determine that a reliability problem exists (see Use Case No. 6),
2. Diagnose the causes of the reliability problem, and
3. Identify promising treatment options for addressing the problem.

As part of the diagnostic process, the analyst needs to be able to identify the facility's primary causes of unreliability and then identify two or three courses of action to address those causes. This approach requires guidance linking causes of unreliability to cost-effective solutions that can be considered.

Use Case No. 4: Reliability Benefits of Alternatives

This use case computes the reliability effects of alternative operational and capacity improvements for addressing reliability problems, including traditional capacity improvements as well as more innovative ATDM measures.

While Use Case No. 3 was primarily about diagnosis, Use Case No. 4 focuses on evaluating candidate treatment options. The analyst fleshes out possible treatments, estimates their effectiveness, and estimates their costs. This analysis requires procedures and parameters for computing the effects of capacity, operational, and ATDM improvements on existing or predicted reliability.

Once an agency has performed enough of these analyses, it can probably develop its own Case No. 3 diagnosis chart with locally specific treatment options.

Use Case No. 5: Prioritizing Improvements

This use case applies reliability performance measures in combination with other performance measures to prioritize investments in operational and capacity improvements. Estimation of the relative values of mean travel time improvements and travel time reliability improvements is included in this case.

While this chapter's methodology provides results for only one facility at a time, agencies putting together a regional program will want to combine the results of individual facility analyses (freeways and urban streets) into a prioritized table. In essence, the issue is how to weight the relative benefits of reliability improvements versus more traditional capacity improvements. How much is average travel time worth to the agency and the public, compared with 95th percentile travel time or some other measure of reliability?

Use Case No. 6: Achieving Acceptable Performance

This use case estimates the probability of failure or the probability of achieving acceptable performance. Performance may be reported as achieving a minimum acceptable LOS.

This use defines and determines acceptable and unacceptable reliability performance. Thus, it is a critical input to the diagnostic process of Use Case No. 3. No diagnosis is needed when it is determined that no reliability problem exists. However, if Use Case No. 6 determines that a problem exists, Use Case No. 3 is used to diagnose the causes and identify promising treatment options.

Use Case No. 6 shares much with Case No. 5, but it introduces a new concept, acceptability or failure. The numerical results produced in Use Case No. 5 are compared with some standard—a national, state, or agency-specific standard of acceptable performance.

This use case introduces the concept of defining a standard both as a minimum acceptable performance level (such as LOS or PTI) and as the probability of failing to achieve that level (i.e., probability of failure). The standard is thus defined in two dimensions: a value and a probability of exceeding that value.

Use Case No. 5 deals with numerical outputs that are compared relative to each other (relativistic evaluation). In contrast, Use Case No. 6 compares the numerical outputs with an absolute standard (failure analysis).

Use Case No. 7: Modeling Choice

This use case applies HCM reliability methods in support of the development and calibration of a route choice model that can distinguish the differing levels of reliability between a tolled and an untolled facility. The HCM reliability method is applied repeatedly at different levels of demand to develop one or more formulas for predicting how travel time variance varies with demand by facility type. This approach is particularly useful for developing route choice models that trade off the greater reliability of tolled roads against less reliable untolled roads. The resulting demand–reliability equations then become inputs to a demand model’s route choice (toll versus nontoll) algorithm.

Use Case No. 8: Improved Demand Modeling

This use case applies HCM methods to develop volume–reliability curves by facility type for use in a demand modeling environment to estimate reliability and to improve destination, time-of-day, mode choice, and route choice models.

USE OF ALTERNATIVE TOOLS

In some cases, a finer temporal sensitivity to dynamic changes in the system will be required for a reliability analysis than can be provided by the typical 15-min analysis period used by HCM methods. This situation may occur in evaluating traffic-responsive signal timing, traffic adaptive control, dynamic ramp metering, dynamic congestion pricing, or measures affecting the prevalence or duration of incidents with less than 10-min durations. There may also be scenarios and configurations that the HCM cannot address, such as complex merging and diverging freeway sections.

For such situations, this chapter’s conceptual framework for evaluating travel time reliability can be applied to alternative analysis tools. The same conceptual approach of generating scenarios, assigning scenario probabilities, evaluating scenario performance, and summarizing the results applies when alternative analysis tools, such as microsimulation, are used to estimate the reliability effects of operations improvements.

Before embarking on the use of alternative tools for reliability analysis, the analyst should consider the much greater analytical demands imposed by a reliability analysis following this chapter's conceptual analysis framework. Thousands of scenarios may need to be analyzed with the alternative tool in addition to the number of replications per scenario required by the tool itself to establish average conditions. Extracting and summarizing the results from numerous applications of the alternative tool may be a significant task.

If a microscopic simulation tool is used, some portions of this chapter's analysis framework that were fit to the HCM's 15-min analysis periods and tailored to the HCM's speed–flow curves will no longer be needed:

- Scenarios may be defined differently from and may be of longer or shorter duration than those used in HCM analysis.
- Incident start times and durations will no longer need to be rounded to the nearest 15-min analysis period.
- Weather start times and durations will no longer need to be rounded to the nearest 15-min analysis period.
- Demand will no longer need to be held constant for the duration of the 15-min analysis period.
- The freeway and urban street peak hour factors used to identify the peak 15-min flow rate within the hour will no longer be applied. They will be replaced with the analysis tool's built-in randomization process.
- The urban street randomization factor for 15-min demands will no longer be applicable. It will be replaced with the analysis tool's built-in randomization process.
- This chapter's recommended urban street saturation flow rate adjustments, freeway capacity adjustment factors, and free-flow speed adjustment factors for weather events and incidents will have to be converted by the analyst to the microsimulation model equivalents: desired speed distribution and desired headway distribution. Acceleration and deceleration rates will also be affected for some weather events.
- This chapter's recommended freeway speed–flow curves for weather events and incidents will be replaced with adjustments to the model's car-following parameters, such as desired free-flow speed, saturation headway, and start-up lost time. Unlike incidents, which the tool's car-following logic can take care of, weather is modeled by adjusting the car-following parameters through weather adjustment factors before the scenarios are run. Application guidance and typical factors are provided in FHWA's *Traffic Analysis Toolbox* (*15*).

If a less disaggregate tool is used (e.g., mesoscopic simulation analysis tool, dynamic traffic assignment tool, demand forecasting tool), many of this chapter's adaptations of the conceptual analysis framework to the HCM may still be appropriate or may need to be aggregated further. The analyst should consult the appropriate tool documentation and determine what further adaptations of the conceptual analysis framework might be required to apply the alternative tool to reliability analysis.

6. EXAMPLE PROBLEMS

The example problems in this section (listed in Exhibit 36-36) demonstrate the application of the freeway facility (Example Problems 1 through 5) and urban street (Example Problems 6 and 7) reliability methods. They illustrate the general process of applying the methods that is described in this chapter, but they incorporate details about selected calculations that are drawn from Chapter 37, Travel Time Reliability: Supplemental. An additional freeway example problem is found in Chapter 37.

An additional freeway example problem is found in Chapter 37.

Exhibit 36-36
List of Example Problems

Problem Number	Description	Application
1	Freeway facility reliability under existing conditions	Operational analysis
2	Freeway facility reliability with a geometric treatment	Planning analysis
3	Freeway facility reliability with incident management	Planning analysis
4	Freeway facility reliability with a safety treatment	Planning analysis
5	Freeway facility reliability with demand management	Planning analysis
6	Urban street reliability under existing conditions	Operational analysis
7	Urban street reliability strategy evaluation	Planning analysis

EXAMPLE PROBLEM 1: RELIABILITY EVALUATION OF AN EXISTING FREEWAY FACILITY

This example problem uses the same 6-mi facility used in Example Problem 1 in Chapter 10. For completeness, the schematic of the facility (Exhibit 10-25) is repeated below in Exhibit 36-37. The facility consists of 11 segments with the properties indicated in Exhibit 36-38. Other facility characteristics are identical to those given in Chapter 10's Example Problem 1, except that the study period in this example has been extended from 75 to 180 min.

Exhibit 36-37
Example Problem 1: Freeway Facility Schematic

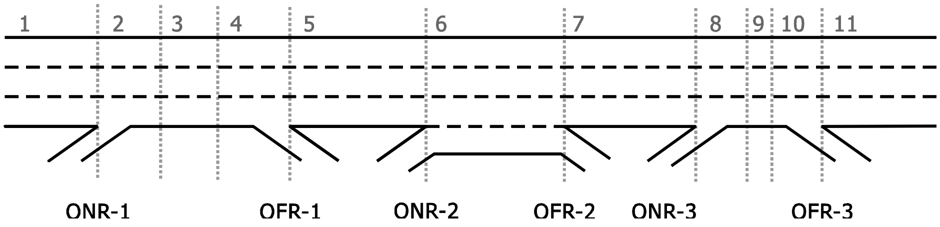


Exhibit 36-38
Example Problem 1: Freeway Facility Segment Properties

Segment No.	1	2	3	4	5	6	7	8	9	10	11
Segment type	B	ONR	B	OFR	B	B or W	B	ONR	R	OFR	B
Segment length (ft)	5,280	1,500	2,280	1,500	5,280	2,640	5,280	1,140	360	1,140	5,280
No. of lanes	3	3	3	3	3	4	3	3	3	3	3

Notes: B = basic freeway segment; W = weaving segment; ONR = on-ramp (merge) segment; OFR = off-ramp (diverge) segment; R = overlapping ramp segment.

This and the following four example problems illustrate

1. Calculation of a variety of reliability statistics for a freeway facility using the minimum required data;
2. Identification of key reliability problems on the facility; and
3. The testing of a number of operational, design, and safety strategies intended to enhance the facility's reliability.

Input Data

This example illustrates the use of defaults and lookup tables to substitute for desirable but difficult-to-obtain data. Minimum facility inputs for the example problem include the following.

Facility Geometry

All of the geometric information about the facility normally required for an HCM freeway facility analysis (Chapters 10 through 13) is also required for a reliability analysis. These data are supplied as part of the base dataset.

Study Parameters

These parameters specify the study period, the reliability reporting period, and the date represented by the traffic demand data used in the base dataset.

The study period in this example is 4 to 7 p.m., which covers the p.m. peak hour and shoulder periods. Recurring congestion is typically present in the study direction of this facility during that period, which is why it is selected for reliability analysis. The reliability reporting period is set as all weekdays in the calendar year. (For simplicity in this example, holidays have not been removed from the reliability reporting period.) The demand data are reflective of AADT.

Base Demand

Demand flow rates (in vehicles per hour) are supplied for each 15-min analysis period in the base dataset. Care should be taken that demand data are measured upstream of any queued traffic. If necessary, demand can be estimated as the sum of departing volume and the change in the queue size at a recurring bottleneck, as described in the Oversaturated Segment Evaluation section of Chapter 25, Freeway Facilities: Supplemental.

Exhibit 36-39 provides the twelve 15-min demand flow rates required for the entire 3-h study period.

Exhibit 36-39
Example Problem 1: Demand Flow Rates (veh/h) by Analysis Period in the Base Dataset

Analysis Period	Demand Entry Flow Rate	On-Ramp 1	On-Ramp 2	On-Ramp 3	Off-Ramp 1	Off-Ramp 2	Off-Ramp 3
1	3,095	270	270	270	180	270	180
2	3,595	360	360	360	270	360	270
3	4,175	360	450	450	270	360	270
4	4,505	450	540	450	270	360	270
5	4,955	540	720	540	360	360	270
6	5,225	630	810	630	270	360	450
7	4,685	360	360	450	270	360	270
8	3,785	180	270	270	270	180	180
9	3,305	180	270	270	270	180	180
10	2,805	180	270	270	270	180	180
11	2,455	180	180	180	270	180	180
12	2,405	180	180	180	180	180	180

Incident Data

Detailed incident logs are not available for this facility, but local data are available about the facility's crash rate: 150 crashes per 100 million VMT. Furthermore, an earlier study conducted by the state that the facility is located in found that an average of seven incidents occur for every crash.

Computational Steps

Base Dataset Analysis

The Chapter 10 freeway facility methodology is applied to the base dataset to make sure that the specified facility boundaries and study period are sufficient to cover any bottlenecks and queues. In addition, because incident data are supplied in the form of a facility crash rate, the VMT associated with the base dataset is calculated so that incident probabilities can be calculated in a subsequent step. In this case, 71,501 VMT occur on the facility over the 3-h base study period. The performance measures normally output by the Chapter 10 methodology are compiled for each combination of segment and analysis period during the study period and stored for later use. In particular, the facility operates just under capacity, with a maximum demand-to-capacity (*d*/*c*) ratio of 0.99 in Segments 7–10.

Incorporating Demand Variability

Exhibit 36-40 provides demand ratios relative to AADT by month and day, derived from a permanent traffic recorder on the facility. Because the demand ratios are based on AADT and because the base dataset demands represent AADT demands, the demand multiplier is 1.00.

Exhibit 36-40
Example Problem 1: Demand Ratios Relative to AADT

Month	Monday	Tuesday	Wednesday	Thursday	Friday
January	1.015	0.971	1.018	1.018	1.022
February	1.030	1.020	1.029	1.016	0.995
March	1.098	1.105	1.105	1.113	1.142
April	1.143	1.105	1.105	1.105	1.132
May	1.132	1.113	1.113	1.113	1.132
June	1.120	1.088	1.088	1.089	1.125
July	1.128	1.096	1.088	1.088	1.120
August	1.120	1.088	1.092	1.089	1.134
September	1.066	1.058	1.058	1.058	1.078
October	1.085	1.060	1.060	1.058	1.091
November	1.053	1.060	1.058	1.060	1.047
December	1.031	1.023	1.022	1.022	1.030

An inspection of these demand patterns indicates two distinct weekday patterns: (*a*) Tuesdays, Wednesdays, and Thursdays have similar volumes across a given month, as do (*b*) Mondays and Fridays. Furthermore, traffic demands are relatively similar across seasons: December–February (winter), March–May (spring), June–August (summer), and September–November (fall). Therefore, the analyst may choose to consolidate the 5 days × 12 months = 60 demand patterns into a smaller set of 2 × 4 = 8 demand patterns, which will greatly reduce the computation time later in the process. The individual demand ratios within each aggregation are averaged to develop an overall aggregated demand ratio (small differences in the number of days per month are ignored). For example, an aggregated demand ratio for Mondays and Fridays in the fall would be determined by averaging the six individual Monday and Friday demand ratios for September, October, and November, resulting in an aggregated demand ratio of 1.070. For a scenario involving a study period on a Monday in October, the base dataset demands would be multiplied by the demand ratio of 1.070 and divided by the demand multiplier of 1.00, resulting in a 7% increase in the base dataset volumes across all analysis periods for that scenario.

The probability of any given demand pattern is the ratio of the number of days (or hours) in a pattern to the total number of days (or hours) in the reliability reporting period. For example, the demand pattern representing Mondays and Fridays in the fall includes 26 weekdays. There are 261 weekdays in the reliability reporting period; thus, the probability of this demand pattern is 26 / 261 or approximately 10%.

Incorporating Weather Variability

In the absence of facility-specific weather data, the default weather data for the metropolitan area closest to the facility are used. Because the demand data were condensed from 12 months to four seasons in the previous step, the probabilities and average durations of each type of weather event are also condensed into four seasons by averaging the monthly values.

In the absence of local data, the default CAF and SAF values given in Exhibit 36-26 for each weather event for a free-flow speed of 60 mi/h are used. These values are applied in a later step to each scenario involving a severe weather event. Exhibit 36-41 summarizes the probabilities of each weather event by season, and Exhibit 36-42 summarizes the CAF, SAF, and event duration values associated with each weather event.

Exhibit 36-41
Example Problem 1: Weather Event Probabilities by Season

	Weather Event Probability (%)			
Weather Event	**Winter**	**Spring**	**Summer**	**Fall**
Medium rain	0.80	1.01	0.71	0.86
Heavy rain	0.47	0.81	1.33	0.68
Light snow	0.91	0.00	0.00	0.00
Light–medium snow	0.29	0.00	0.00	0.00
Medium–heavy snow	0.04	0.00	0.00	0.00
Heavy snow	0.00	0.00	0.00	0.00
Severe cold	0.00	0.00	0.00	0.00
Low visibility	0.97	0.12	0.16	0.34
Very low visibility	0.00	0.00	0.00	0.00
Minimal visibility	0.44	0.10	0.00	0.03
Non–severe weather	96.09	97.95	97.80	98.08

Exhibit 36-42
Example Problem 1: CAF, SAF, and Event Duration Values Associated with Weather Events

Weather Event	CAF	SAF	Average Duration (min)
Medium rain	0.93	0.95	40.2
Heavy rain	0.88	0.93	33.7
Light snow	0.96	0.92	93.1
Light–medium snow	0.94	0.90	33.4
Medium–heavy snow	0.91	0.88	21.7
Heavy snow	0.78	0.86	7.3
Severe cold	0.92	0.95	0.0
Low visibility	0.90	0.95	76.2
Very low visibility	0.88	0.94	0.0
Minimal visibility	0.90	0.94	145
Non–severe weather	1.00	1.00	N/A

Note: N/A = not applicable.

Incorporating Incident Variability

For an existing freeway facility such as this one, detailed incident logs that can be used to develop monthly or seasonal probabilities of various incident severities are desirable. However, in this case, incident logs of sufficient detail are not available.

Therefore, incident probabilities and severities are estimated by the alternative method of using local crash rates and ratios of incidents to crashes, in combination with default values. This process is described in the Freeway Incident Prediction section of Chapter 37, Travel Time Reliability: Supplemental. In summary, the expected number of incidents during a study period under a specified demand pattern is the product of the crash rate, the local incident-to-crash ratio, the demand volume during the study period, and the facility length.

To continue with the example of the demand pattern associated with Mondays and Fridays in the fall, the crash rate is 150 crashes per 100 million VMT and the ratio of incidents to crashes is 7 (from the input incident data), the base study period VMT is 71,501 (from the Base Dataset Analysis step), and the demand ratio is 1.070 and the demand multiplier is 1.00 (from the Incorporating Demand Variability step).

The expected number of incidents is then $(150 \times 10^{-8}) \times 7 \times 71{,}501 \times (1.07 / 1.00) = 0.803$ incident per 3-h study period.

Estimating the time-based probability of a specific incident type requires data on the fraction of all incidents of that type and their average duration. In the absence of local data, the default values from Exhibit 36-24 and Exhibit 36-25 are used. For example, from Exhibit 36-24, 75% of all incidents nationally are shoulder-closure incidents. Because full-facility closures (i.e., all three lanes in the case of this facility) are not modeled by the reliability method, the probability of a three-or-more-lane closure is combined with that of a two-lane closure, resulting in a 5% probability of a two-lane closure. The average duration of shoulder-closure incidents is 32 min.

The time-based probability of a shoulder closure incident for this demand pattern is given in Chapter 37 (Equation 37-5) as

$$P_{sc,fall,M/F} = 1 - e^{-(n_{fall,M/F} g_{sc})(t_{sc}/t_{sp})}$$

where

$P_{sc,fall,M/F}$ = time-based probability of a shoulder closure incident for the "fall, Monday and Friday" demand pattern;

$n_{fall,M/F}$ = expected number of incidents per study period for the "fall, Monday and Friday" demand pattern;

g_{sc} = proportion of all incidents that are shoulder-closure incidents;

t_{sc} = average duration of a shoulder-closure incident (min or h); and

t_{sp} = study period duration (min or h).

With 0.803 incident expected per study period for this demand pattern, 75% of which are shoulder-closure incidents, a 32-min average duration for shoulder-closure incidents, and a 180-min study period duration, the probability of a shoulder-closure incident for this demand pattern is the following:

$$P_{sc,fall,M/F} = 1 - e^{-(0.803 \times 0.75)(32/180)} = 0.1015$$

Exhibit 36-43 presents the full matrix of incident probabilities by severity and demand pattern obtained by applying this equation to all combinations of incidents and demand patterns.

Exhibit 36-43
Example Problem 1: Incident Time-Based Probabilities by Demand Pattern

Demand Pattern	Incident Time-Based Probability (%) No Incident	Shoulder Closure	One Lane Closed	Two Lanes Closed
Winter, M/F	86.32	9.71	2.85	1.12
Winter, Tu/W/Th	86.39	9.66	2.84	1.12
Spring, M/F	84.90	10.70	3.16	1.24
Spring, Tu/W/Th	85.18	10.51	3.10	1.22
Summer, M/F	84.97	10.65	3.14	1.24
Summer, Tu/W/Th	85.43	10.33	3.04	1.20
Fall, M/F	85.68	10.15	2.99	1.18
Fall, Tu/W/Th	85.90	10.00	2.94	1.16

Notes: M = Monday; Tu = Tuesday; W = Wednesday; Th = Thursday; F = Friday.

Scenario Generation

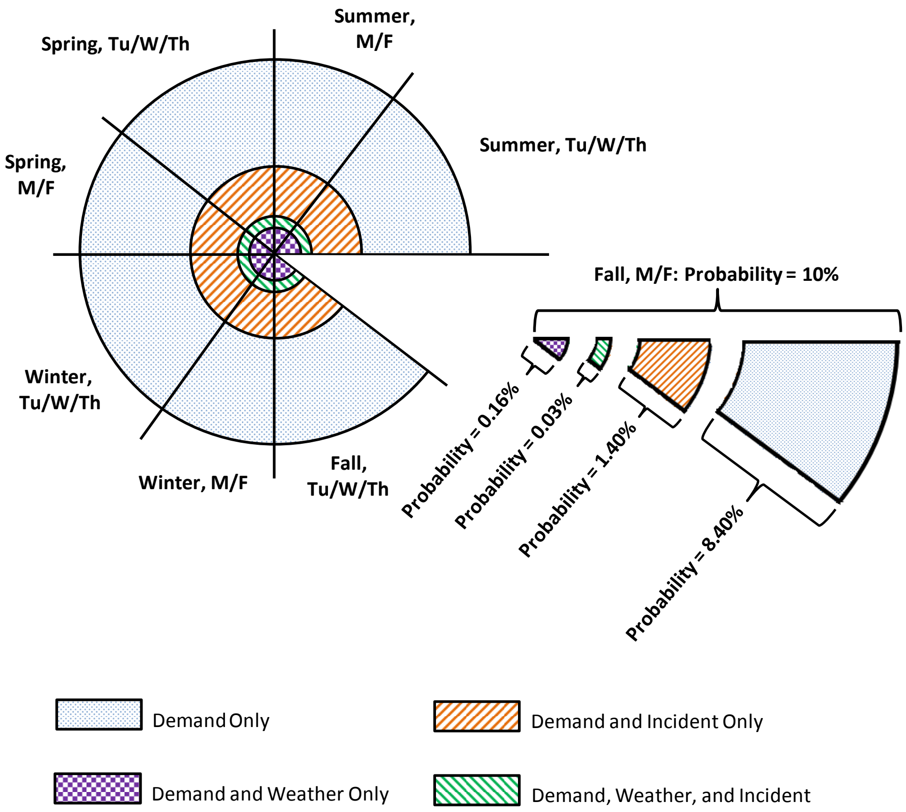
Now that the probabilities of various demand patterns, severe weather events, and incident types have been determined, the scenario generator creates the one operational scenario for each possible combination of pattern and event, along with the scenario's overall probability and its operational (i.e., demand and capacity) characteristics. The resulting combinations of operational scenarios and their relative probabilities are illustrated in Exhibit 36-44.

An example of how these probabilities are calculated is now given for the demand pattern representing Mondays and Fridays in the fall. For this demand pattern, the sum of the time-based probabilities for all incidents is 14.32%, from Exhibit 36-43. Similarly, the sum of the time-based probabilities for all severe weather events in the fall is 1.92%, from Exhibit 36-41.

Since the freeway reliability methodology assumes independence between the events, the joint probability of a combination of events is simply the product of the individual events' probability. As an illustration, some of the relevant base probabilities are calculated for Mondays and Fridays in the fall. Note that this demand pattern occurs for 10% of the days in the reliability reporting period, as determined earlier. Then the following can be computed:

- P (Monday/Friday fall demand, no incident, non–severe weather) = $0.10 \times 0.8568 \times 0.9808 = 8.40\%$,
- P (Monday/Friday fall demand, no incident, severe weather) = $0.10 \times 0.8568 \times (1 - 0.9808) = 0.16\%$,
- P (Monday/Friday fall demand, incident, non–severe weather) = $0.10 \times (1 - 0.8568) \times 0.9808 = 1.40\%$, and
- P (Monday/Friday fall demand, incident, severe weather) = $0.10 \times (1 - 0.8568) \times (1 - 0.9808) = 0.03\%$.

Exhibit 36-44
Example Problem 1: Probabilities of Combinations of Demand, Weather, and Incidents



As a check, these probabilities add up to 10%, after rounding errors are accounted for. The "Study Period and Detailed Scenario Generation" procedure given in Chapter 37 is applied to create the final set of the scenarios. This procedure ensures consistency between the stated duration of events (weather or incidents) and their probability. For example, most of the time in a "demand and incident only" scenario consists of "demand only" time (i.e., the portion of a "demand and incident scenario" without an incident). The unadjusted probability for the "demand and incident scenario" therefore represents the probability that an incident will occur at any point during the study period, while the adjusted probability represents the probability that an incident is present during a specific 15-min analysis period.

In this case, this process yields a total of 1,928 operational scenarios incorporating all variations in demand, weather, and incidents, as shown in the "no exclusion" column of Exhibit 36-45.

Exhibit 36-45
Example Problem 1: Number and Types of Generated Scenarios

	Number of Scenarios		Percentage of Scenarios	
Scenario Description	**No Exclusion**	**0.01% Inclusion Threshold**	**No Exclusion**	**0.01% Inclusion Threshold**
Demand-only variations	8	8	0.4	1.3
Demand and weather variations	72	60	3.7	10.0
Demand and incident variations	336	336	17.4	55.8
Demand, weather, and incidents	1,512	198	78.4	32.9
Total	1,928	602	100	100

The method allows the analyst to discard very-low-probability scenarios by applying an inclusion threshold. This approach entails a risk of missing some of the very severe scenarios (e.g., multiple lane closures in a snowstorm) that fall below the inclusion threshold; however, these scenarios may be so rare that they do not occur every year (or occur only every few years). If low-probability scenarios are discarded, the probabilities of all discarded scenarios are proportionally reassigned to the remaining scenarios.

The main reason for choosing this approach is to reduce the number of scenarios evaluated with the Chapter 10 freeway facilities methodology and the corresponding analysis time significantly. If the analysis time is not an issue, there is no need to discard scenarios. Exhibit 36-45 shows the number of scenarios that would be generated if a 0.01% probability threshold were applied; it indicates that the number of scenarios to be evaluated would drop by more than two-thirds.

In summary, a detailed scenario will contain the following attributes, many of which are converted into a set of adjustments to free-flow speed, capacity, and possibly demand. The following items represent the minimum information needed to characterize a detailed scenario:

- Scenario number;
- Adjusted scenario probability;
- Demand pattern number;
- Whether a weather event is present and, if so,
    - Its type (rain, snow, low visibility, etc.),
    - Its duration (average duration only), and
    - Its start time (either at the beginning or halfway in the study period);
- Whether an incident is present and, if so,
    - Its severity (shoulder closure, single or multiple lane closures),
    - Its duration (25th, 50th, and 75th percentile of default distribution),
    - Its start time (either at the beginning or halfway in the study period), and
    - Its location on the facility (three locations, on first, last, and midpoint segments); and
- Whether a combination of weather and incident events is present (combinations of the above two conditions).

Applying the Chapter 10 Procedure

Each scenario is converted into a matrix of adjusted demands, segment capacities, free-flow speeds, and number of open lanes that are applied to the base database values for the specific segments and analysis periods. The input data for each scenario are then provided one scenario at a time to the Chapter 10 freeway facilities method, which generates an average travel time for each analysis period within the scenario's defined study period, along with the other performance measures that the Chapter 10 method produces.

After all of the scenarios have been analyzed, a VMT-weighted probability value is applied to each scenario travel time. The resulting distribution of travel times can be used to generate a variety of reliability performance measures.

Results and Discussion

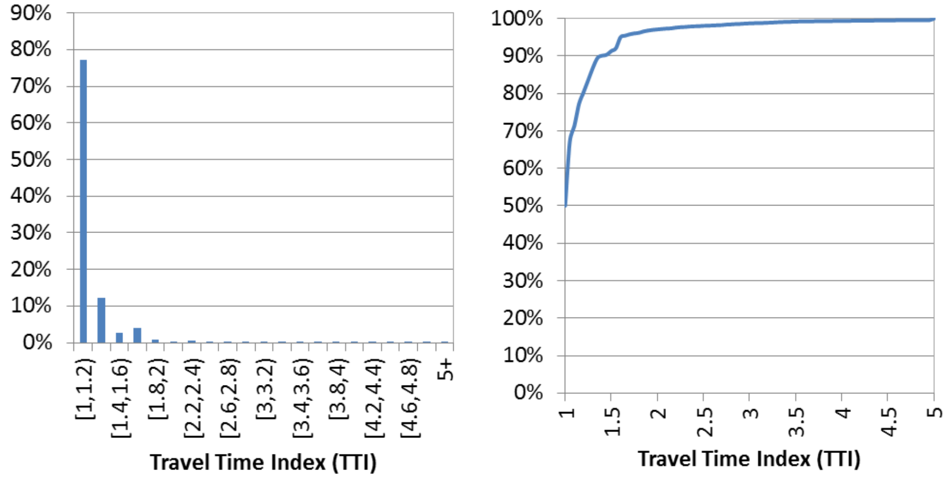
Exhibit 36-46 provides key reliability performance measure results for this example problem. The scenario inclusion threshold was 0.01%, which led to a total of 602 scenarios. The exhibit provides the results for only the base conditions (representing a standard HCM freeway facilities analysis for conditions representative of AADT demands) along with the results from running all 602 scenarios, covering 7,224 analysis periods. Exhibit 36-47 shows the generated probability and cumulative distributions of TTI for this example problem.

Exhibit 36-46
Example Problem 1: Summary Reliability Performance Measure Results

Reliability Performance Measure	Value for Base Scenario	Value from All Scenarios	Percent Difference
Mean facility TTI (corresponding speed, mi/h)	1.04 (57.7)	1.21 (49.7)	+16
PTI (corresponding speed, mi/h)	Unavailable	1.65 (36.4)	N/A
Maximum observed facility TTI (speed, mi/h)	1.09 (55.0)	37.1 (1.6)	+3,300
Misery index (corresponding speed, mi/h)	Unavailable	3.00 (20.0)	N/A
Reliability rating (%)	Unavailable	85.0	N/A
Average VHD per analysis period	4.0	21.9	+443
Average VHD due to recurring congestion	Unavailable	9.3	N/A
Average VHD due to nonrecurring congestion	Unavailable	12.6	N/A

Notes: N/A = not applicable; PTI = planning time index; TTI = travel time index; VHD = vehicle hours of delay.

Exhibit 36-47
Example Problem 1: VMT-Weighted TTI Probability and Cumulative Distribution Functions



(a) Probability Distribution Function (b) Cumulative Distribution Function

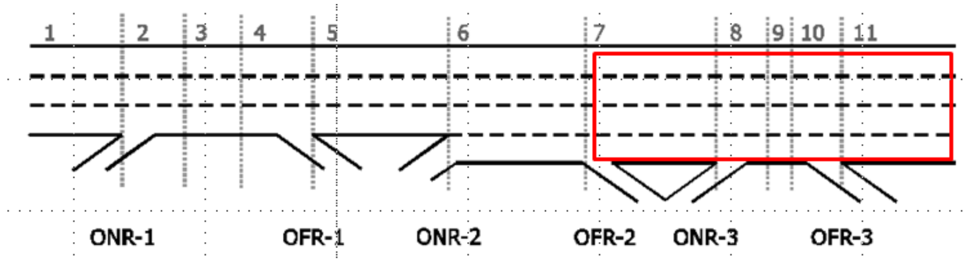
These results demonstrate that focusing on a single study period tends to provide an incomplete and biased picture of facility performance over the course of the reliability reporting period. When only a single study period is analyzed, none of the reliability statistics can be computed, and the impacts of incidents and weather are typically not taken into account. For an operating agency, knowing that 85% of the facility's VMT during the p.m. peak period operates at a speed of 45 mi/h or higher is an important benchmark. It is also clear that much of the facility's delay is due to demand variability and the effect of weather and incidents.

Whether using a scenario inclusion threshold of 0.01% substantially affected the reliability performance measure results can be considered. When all 1,928 scenarios are evaluated, the mean TTI remains at 1.21, the PTI increases from 1.65 to 1.67, the misery index increases from 3.00 to 3.04, and the reliability rating decreases from 85.04% to 84.85%. None of these changes would be expected to alter any conclusions or comparisons materially.

EXAMPLE PROBLEM 2: GEOMETRIC TREATMENT

In this example, the freeway facility from Example Problem 1 is widened by a lane in Segments 7–11. These segments operated close to capacity in the base scenario and were definitely over capacity in scenarios with severe weather or incident conditions. The revised geometry also improves the operation of weaving Segment 6, since no lane changes are required of traffic entering at On-Ramp 2. Exhibit 36-48 provides a schematic of the freeway facility.

Exhibit 36-48
Example Problem 2: Freeway Facility Schematic



Data Inputs

All the input data used in Example Problem 1 remain unchanged, except of course for the number of lanes on the facility. The only other exception is the consideration of having a three-lane-closure incident scenario in the four-lane section of the facility. From Exhibit 36-24, the probability of a two-lane closure in this portion of the facility is 3.1%, while the probability of a three-lane closure is 1.9%.

Results and Discussion

As a result of the lane additions and the emergence of an additional set of scenarios with three-lane closures, the total number of possible scenarios increases from 1,928 in Example Problem 1 to 2,192 here. Using a scenario inclusion threshold of 0.01% changes the number of scenarios from 602 in Example Problem 1 to 650 here. Exhibit 36-49 provides key reliability performance measure results for this example problem.

Exhibit 36-49
Example Problem 2: Summary Reliability Performance Measure Results

Reliability Performance Measure	Value for Base Scenario	Value from All Scenarios	Percent Difference
Mean facility TTI (corresponding speed, mi/h)	1.03 (58.3)	1.09 (55.0)	+6
PTI (corresponding speed, mi/h)	Unavailable	1.16 (51.7)	N/A
Maximum observed facility TTI (speed, mi/h)	1.04 (57.7)	37.6 (1.6)	+3,500
Misery index (corresponding speed, mi/h)	Unavailable	2.04 (29.4)	N/A
Reliability rating (%)	Unavailable	97.4	N/A
Average VHD per analysis period	3.2	8.9	+179
Average VHD due to recurring congestion	Unavailable	2.8	N/A
Average VHD due to nonrecurring congestion	Unavailable	6.1	N/A

Notes: N/A = not applicable; PTI = planning time index; TTI = travel time index; VHD = vehicle hours of delay.

The results of this example problem again confirm the value of a time-extended facility analysis. Had the analyst relied only on the seed file results from one representative day, the mean TTI would have decreased from 1.04 in the base case to 1.03 in the improved case, or conversely the speed would have been predicted to increase from 57.7 to 58.3 mi/h—barely a perceptible change, and certainly not enough to recommend the major improvement.

On the other hand, the mean TTI across the reliability reporting period decreases from 1.21 to 1.09, corresponding to a speed improvement from 49.7 to 55.0 mi/h—more than a 10% increase and perhaps enough to justify the improvement, once non-reliability-related factors are taken into account. Similar results occur for most other performance measures.

One lesson learned from this exercise is that benefits derived from capacity improvements could be substantially understated if they are based only on operations on a typical day. The geometric improvement implemented in this example problem provided a good "performance buffer" for severe weather and incident events that reduce the facility's capacity.

EXAMPLE PROBLEM 3: INCIDENT MANAGEMENT TREATMENT

This example problem illustrates the analysis of a nonconstruction alternative that focuses on improved incident management strategies. In this example, the size of the motorist response fleet is increased and communication is improved between the various stakeholders (e.g., traffic management center, emergency responders, and motorist response fleet), allowing faster clearance of incidents than before.

Data Inputs

All the input data used in Example Problem 1 remain unchanged, except for the assumed incident duration and standard deviation. The default incident duration values given in Exhibit 36-25 are modified as shown in Exhibit 36-50, on the basis of the analyst's review of a peer agency's incident management program. Note that these durations have been created for the purposes of this example problem and do not necessarily reflect results that would be obtained in a real-world situation.

Exhibit 36-50
Example Problem 3: Assumed Freeway Incident Durations (min)

Month	Incident Type Shoulder Closed	1 Lane Closed	2 Lanes Closed
25th percentile	14	16	28
50th percentile	26	27	39
75th percentile	38	38	50

Results and Discussion

The key congestion and reliability statistics for this example problem are summarized in Exhibit 36-51. The total number of possible scenarios decreases from 1,928 in Example Problem 1 to 1,664 here; use of a scenario inclusion threshold of 0.01% decreases the number of scenarios from 602 to 442. This result occurs because more combinations of demand, weather, and incidents have probabilities less than 0.01%.

Exhibit 36-51
Example Problem 3: Summary Reliability Performance Measure Results

Reliability Performance Measure	Value for Base Scenario	Value from All Scenarios	Percent Difference
Mean facility TTI (corresponding speed, mi/h)	1.04 (57.7)	1.17 (51.3)	+13
PTI (corresponding speed, mi/h)	Unavailable	1.61 (37.3)	N/A
Maximum observed facility TTI (speed, mi/h)	1.09 (55.5)	32.2 (1.86)	+2,850
Misery index (corresponding speed, mi/h)	Unavailable	2.47 (24.3)	N/A
Reliability rating (%)	Unavailable	87.3	N/A
Average VHD per analysis period	4.0	17.7	+340
Average VHD due to recurring congestion	Unavailable	9.6	N/A
Average VHD due to nonrecurring congestion	Unavailable	8.1	N/A

Notes: N/A = not applicable; PTI = planning time index; TTI = travel time index; VHD = vehicle hours of delay.

The facility's operations generally show some slight operational improvements—for example, a drop in the PTI from 1.65 to 1.61—compared with Example Problem 1. The largest improvement is in the misery index, which improves from 3.00 (20 mi/h) to 2.47 (24.3 mi/h), a 20% improvement. It appears that the proposed treatment, while not necessarily affecting average operations, would reduce the severity of extreme cases combining weather and incident effects. The analyst should also bear in mind that within the Chapter 10 freeway facility methodology, all incident durations must be entered in multiples of 15 min. As a result, the impact of the reduced incident duration time may not be fully captured by the model structure. However, a traditional HCM analysis would not have captured any effect: the base scenario results from Example Problems 1 and 3 are the same. The effectiveness of incident management treatments on a facility can only be evaluated by incorporating the effects of incidents on travel time, as this chapter's reliability method does.

EXAMPLE PROBLEM 4: SAFETY TREATMENT

This example problem illustrates the analysis of safety-related treatments that reduce the likelihood of incidents occurring. In this case, a road safety audit has identified a package of potential safety improvements along the facility; this example problem evaluates the combined effect of these improvements on reliability.

Data Inputs

All the input data used in Example Problem 1 remain unchanged except for the assumed incident probabilities given in Exhibit 36-43. The incident probabilities are modified as shown in Exhibit 36-52, on the basis of the analyst's review of a peer agency's results following the implementation of a similar package of treatments. Note that these incident probabilities have been created for the purposes of this example problem and do not necessarily reflect results that would be obtained in a real-world situation.

Exhibit 36-52
Example Problem 4: Incident Probabilities by Demand Pattern

	Incident Probability (%)			
Demand Pattern	**No Incident**	**Shoulder Closure**	**One Lane Closed**	**Two Lanes Closed**
Winter, M/F	92.20	5.56	1.61	0.63
Winter, Tu/W/Th	92.25	5.53	1.60	0.63
Spring, M/F	91.38	6.14	1.78	0.70
Spring, Tu/W/Th	91.54	6.03	1.75	0.68
Summer, M/F	91.42	6.11	1.77	0.69
Summer, Tu/W/Th	91.69	5.93	1.72	0.67
Fall, M/F	91.84	5.82	1.68	0.66
Fall, Tu/W/Th	91.96	5.73	1.66	0.65

Notes: M = Monday; Tu = Tuesday; W = Wednesday; Th = Thursday; F = Friday.

Results and Discussion

The key congestion and reliability statistics for this example problem are summarized in Exhibit 36-53. The total number of possible scenarios remains 1,928; use of a scenario inclusion threshold of 0.01% decreases the number of scenarios from 602 to 424. This result occurs because more combinations of demand, weather, and incidents have probabilities less than 0.01%.

Exhibit 36-53
Example Problem 4: Summary Reliability Performance Measure Results

Reliability Performance Measure	Value for Base Scenario	Value from All Scenarios	Percent Difference
Mean facility TTI (corresponding speed, mi/h)	1.04 (57.7)	1.16 (51.0)	+12
PTI (corresponding speed, mi/h)	Unavailable	1.61 (37.3)	N/A
Maximum observed facility TTI (speed, mi/h)	1.09 (55.5)	37.1 (1.6)	+3,300
Misery index (corresponding speed, mi/h)	Unavailable	2.53 (23.8)	N/A
Reliability rating (%)	Unavailable	87.7	N/A
Average VHD per analysis period	4.0	17.4	+333
Average VHD due to recurring congestion	Unavailable	10.0	N/A
Average VHD due to nonrecurring congestion	Unavailable	7.4	N/A

Notes: N/A = not applicable; PTI = planning time index; TTI = travel time index; VHD = vehicle hours of delay.

As in Example Problem 3, average facility operations appear to improve slightly compared with Example Problem 1. While the PTI drops slightly from 1.65 to 1.61, the misery index improves by 18% from 3.00 (20 mi/h) to 2.53 (23.8 mi/h) and the vehicle hours of delay (VHD) drops by 20% from 21.9 to 17.4. The reliability rating improves from 85.0% to 87.7%. As was the case in Example Problem 3, a traditional HCM analysis would not have captured any effect from the safety treatment, since the base scenario results of Example Problems 1 and 4 are the same.

EXAMPLE PROBLEM 5: DEMAND MANAGEMENT STRATEGY

In this example problem, demand management techniques are used to shift peak hour demand to the shoulder periods. The reduction of peak period demand provides a capacity buffer that may be able to absorb some of the capacity-reducing effects of severe weather and incidents.

Data Inputs

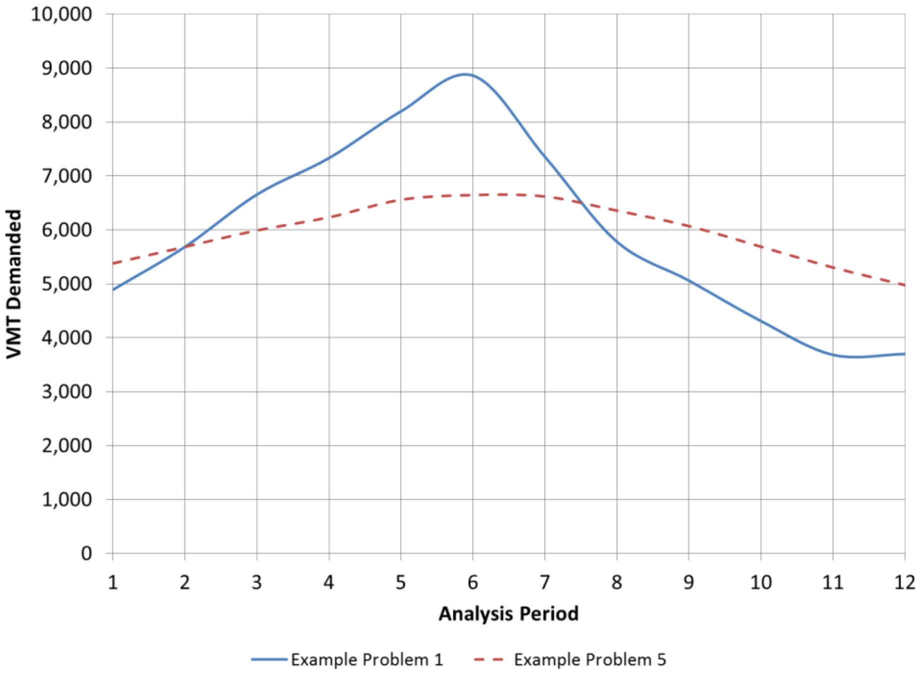
All the input data used in Example Problem 1 remain unchanged, except for the traffic demands given in Exhibit 36-39. These traffic demands are modified as shown in Exhibit 36-54 (flattening the peak), on the basis of the analyst's assumptions about the effectiveness of the demand management strategy. Note that these changes in demand have been created for the purposes of this example problem and do not necessarily reflect results that would be obtained in a real-world situation.

Exhibit 36-54
Example Problem 5: Demand Flow Rates (veh/h) by Analysis Period in the Base Dataset

Analysis Period	Demand Entry Flow Rate	On-Ramp 1	On-Ramp 2	On-Ramp 3	Off-Ramp 1	Off-Ramp 2	Off-Ramp 3
1	3,405	297	297	297	198	297	198
2	3,595	360	360	360	270	360	270
3	3,758	324	405	405	243	324	243
4	3,829	383	459	383	230	306	230
5	3,964	432	576	432	288	288	216
6	3,919	473	608	473	203	270	338
7	4,217	324	324	405	243	324	243
8	4,164	198	297	297	297	198	198
9	3,966	216	324	324	324	216	216
10	3,703	238	356	356	356	238	238
11	3,535	259	259	259	389	259	259
12	3,236	242	242	242	242	242	242

The VMT remains 71,501, the same as in Example Problem 1, but more demand occurs in the shoulder periods than before and less demand in the peak period. Exhibit 36-55 illustrates the change in demand by analysis period. In Example Problem 1, the demand during Analysis Period 6 was approximately 8,900 VMT, while the new demand as a result of the demand management strategies is approximately 6,800 VMT.

Exhibit 36-55
Example Problem 5: Comparison of VMT Demand by 15-min Analysis Periods



Results and Discussion

Exhibit 36-56 summarizes the key congestion and reliability statistics for Example Problem 5. The total number of possible scenarios remains the same as in Example Problem 1 (1,928 with no scenario exclusion and 602 with a 0.01% scenario inclusion threshold).

Exhibit 36-56
Example Problem 5: Summary Reliability Performance Measure Results

Reliability Performance Measure	Value for Base Scenario	Value from All Scenarios	Percent Difference
Mean facility TTI (corresponding speed, mi/h)	1.04 (57.7)	1.12 (53.6)	+8
PTI (corresponding speed, mi/h)	Unavailable	1.29 (46.5)	N/A
Maximum observed facility TTI (speed, mi/h)	1.09 (55.5)	33.1 (1.8)	+2,900
Misery index (corresponding speed, mi/h)	Unavailable	2.69 (23.5)	N/A
Reliability rating (%)	Unavailable	95.3	N/A
Average VHD per analysis period	4.0	12.5	+211
Average VHD due to recurring congestion	Unavailable	2.9	N/A
Average VHD due to nonrecurring congestion	Unavailable	9.6	N/A

Notes: N/A = not applicable; PTI = planning time index; TTI = travel time index; VHD = vehicle hours of delay.

On average, the facility shows significant operational improvements compared with Example Problem 1. The improvement is not as great as that of Example Problem 2 (the geometric treatment) but is more significant than the improvements from the incident management and safety treatments evaluated in Example Problems 3 and 4, respectively. In particular, both the PTI and the VHD show significant improvements over the 3-h study period, and the misery index improves.

Treatment Comparisons

A side-by-side summary of the treatments' effect in the five example problems on a number of performance measures is given in Exhibit 36-57.

Exhibit 36-57
Example Problem 5: Treatment Summary Comparison

Reliability Performance Measure	**Example Problem 1** Base Condition	**Example Problem 2** Geometric Treatment	**Example Problem 3** Incident Management	**Example Problem 4** Safety Treatment	**Example Problem 5** Demand Management
Mean TTI across all scenarios	1.21	1.09	1.17	1.16	1.12
Facility mean speed (mi/h)	49.7	55.0	51.3	51.0	53.6
PTI	1.65	1.16	1.61	1.61	1.29
Reliability rating (%)	85.0	97.4	87.3	87.7	95.3
Misery index	3.00	2.04	2.47	2.53	2.69
Mean VHD in a 3-h study period	263	108	213	209	150
% VHD due to nonrecurring effects	57%	68%	46%	43%	77%

Several observations emerge from this comparison:

- The lane-add treatment had the strongest effect on performance. The added lane essentially serves as a buffer that helps absorb the shock of capacity-reducing incidents or weather events. Since this is a bottleneck treatment that addresses a recurring congestion problem, the share of delay due to nonrecurring events increased.
- Demand management had the second most beneficial effect on the absorption of the recurring congestion problem.
- The incident management and safety treatments produced similar positive effects compared with the base condition. The interesting difference is that because the incident duration (and standard deviation) was reduced in the incident management case, that treatment yielded a slightly lower misery index than the safety treatment. The misery index is pegged to the most severe cases a user can expect on the facility. In contrast, the safety treatment reduced the overall probability of crashes and incidents. As a result, delays due to nonrecurring congestion had the smallest share of VHD with this treatment.
- Safety treatments and incident management strategies affect the tail of the travel time distribution. The misery index experienced the greatest improvement under these treatments. In contrast, the demand management treatment affects the peak of the travel time distribution. The PTI and mean TTI showed substantial improvements under the demand management strategy.
- In all cases, the treatment benefits far exceeded those that would have been estimated with a traditional HCM analysis that only considers recurring congestion effects during a single study period.
- A host of other treatments related to ATDM can be tested with this chapter's reliability methodology, as long as their impacts can be converted into adjustments to free-flow speed, capacity, traffic demand, or a combination of these items.
- An important limitation of the analysis presented in these examples is the assumption that travel demand is insensitive to severe weather or incident conditions. Under such scenarios, travelers are likely to alter

their route, departure time, or mode, or they may cancel their trip altogether. While the methodology accommodates user-defined changes in demand associated with weather or incidents, that capability was not used in these example problems.

EXAMPLE PROBLEM 6: EXISTING URBAN STREET RELIABILITY

Objective

This example problem illustrates

- The steps involved in calculating reliability statistics for an urban street facility with the minimum required data for the analysis,
- Identification of the key reliability problems on the facility, and
- Diagnosis of the causes (e.g., demand, weather, incidents) of reliability problems on the facility.

Site

The selected site for this example problem is an idealized 3-mi-long principal arterial street in Lincoln, Nebraska. The street is a two-way, four-lane, divided roadway with shoulders. Seven signalized intersections are spaced uniformly at 0.5-mi intervals along the street. The posted speed limit on the major street and the minor streets is 35 mi/h. A portion of this street is shown in Exhibit 36-58. The distances shown are the same for the other segments of the facility.

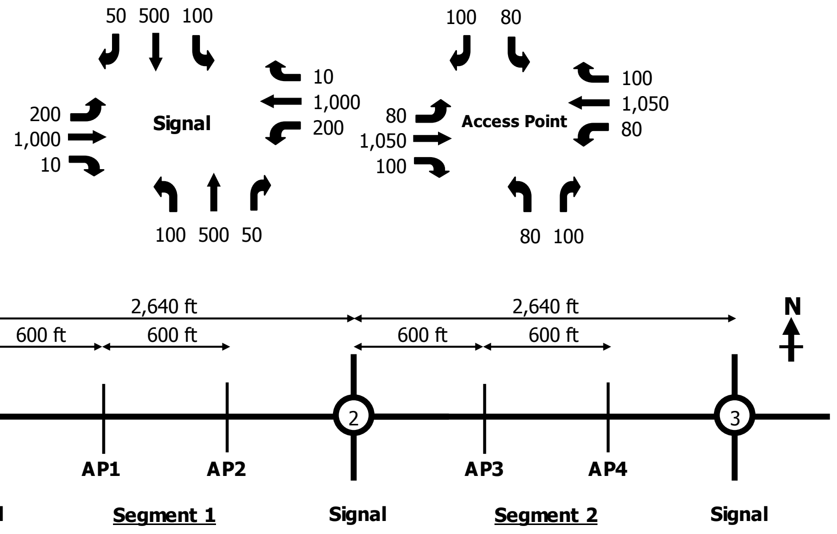


Exhibit 36-58
Example Problem 6: Urban Street Facility

Also shown in Exhibit 36-58 are the traffic movement volumes for each intersection and access point on the facility. Each intersection has the same volume, and each access point has the same volume. Intersection geometry and signal timing are described in a subsequent section.

Required Input Data

This section describes the input data needed for both the reliability methodology and the core HCM urban streets methodology. The dataset that describes conditions where no work zones or special events are present is known as the *base dataset.* Other datasets used to describe work zones or special events are called *alternative datasets.*

Reliability Methodology Input Data

Exhibit 36-59 lists the input data needed for an urban street reliability evaluation. The agency does not collect traffic volume data on a continual basis, so the factors and ratios that describe demand patterns will be defaulted. Traffic counts for one representative day are provided by the analysis and used as the basis for estimating volume during other hours of the year. Lincoln, Nebraska, is one of the communities for which a 10-year summary of weather data is provided, so the default weather data will be used. Incident data are available locally as annual crash frequencies by intersection and street segment. It was determined that the effect of work zones or special events on reliability would not be considered in the evaluation.

HCM Urban Street Methodology Input Data

This subsection describes the data gathered to develop the base dataset. The base dataset contains all of the input data required to conduct an urban street facility analysis with the methodologies described in HCM Chapters 16 through 18. Alternative datasets are not needed because the effects of work zones and special events are not being considered in the evaluation.

Exhibit 36-59
Example Problem 6: Input Data Needs and Sources

Data Category	Input Data Need	Data Value
Time periods	Analysis period Study period Reliability reporting period	15 min 7–10 a.m. Nonholiday weekdays for 1 year
Demand patterns	Hour-of-day factors Day-of-week demand ratio Month-of year demand ratio Demand change due to rain, snow	Will be defaulted
Weather	Rain, snow, and temperature data by month Pavement runoff duration	Will be defaulted
Incidents	Segment and intersection crash frequencies Crash frequency adjustment factors for work zones and special events Factors influencing incident duration	Available locally (See Step 5) Not required (no work zones) Will be defaulted
Work zones and special events	Changes to base conditions (alternative dataset) and schedule	Not required (no work zones)
Nearest city	Required when defaulted weather data used	Lincoln, Nebraska
Geometrics	Presence of shoulder	Yes
Traffic counts	Day and time of traffic counts used in base and alternative datasets	Tuesday, January 4, 7–8 a.m. No alternative datasets required (no work zones)
Functional class	Urban street functional class	Urban principal arterial

Traffic count data for the hour beginning at 7:00 a.m. are available from a recent traffic count taken on a Tuesday, January 4. Weather conditions were clear, and the pavement was dry. The traffic volumes are shown in Exhibit 36-58. They are the same at all seven intersections for this idealized example.

Exhibit 36-60 provides the signal timing data for Intersection No. 1. The other signalized intersections have the same signal timing.

Exhibit 36-60
Example Problem 6: Intersection No. 1 Signal Timing Data

Approach	Eastbound			Westbound			Northbound			Southbound		
Movement	**L**	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**	**L**	**T**	**R**
NEMA movement no.	5	2	12	1	6	16	3	8	18	7	4	14
Volume (veh/h)	200	1000	10	200	1000	10	100	500	50	100	500	50
Lanes	1	2	1	1	2	1	1	2	0	1	2	0
Turn bay length (ft)	200	0	200	200	0	200	200	0	0	200	0	0
Saturation flow rate (veh/h/ln)	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800	1800
Platoon ratio	1.000	1.333	1.000	1.000	1.333	1.000	1.000	1.000	1.000	1.000	1.000	1.000
Initial queue (veh)	0	0	0	0	0	0	0	0	0	0	0	0
Speed limit (mi/h)	--	35	--	--	35	--	--	35	--	--	35	--
Detector length (ft)	40			40	--	--	40	40	--	40	40	--
Lead/lag left-turn phase	Lead	--		Lead	--		Lead	--		Lead	--	
Left-turn mode	Prot.	--		Prot.	--		Pr/Pm	--		Pr/Pm	--	
Passage time (s)	2.0	--		2.0	--		2.0	2.0		2.0	2.0	
Minimum green (s)	5	--		5	--		5	5		5	5	
Change period (Y+Rc) (s)	3.0	4.0		3.0	4.0		3.0	4.0		3.0	4.0	
Phase splits (s)	20.0	35.0		20.0	35.0		20.0	25.0		20.0	25.0	
Max. recall	Off	--		Off	--		Off	Off		Off	Off	
Min. recall	Off	--		Off	--		Off	Off		Off	Off	
Dual entry	No	Yes		No	Yes		No	Yes		No	Yes	
Simultaneous gap out	Yes	Yes		Yes	Yes		Yes	Yes		Yes	Yes	
Dallas phasing	No	No		No	No		No	No		No	No	
Reference phase		2										
Offset (s)		0 or 50										

Notes: L = left turn; T = through; R = right turn; Prot. = protected; Pr/Pm = permissive-protected.
See Chapter 18 for definitions of signal timing variables.

At each signalized intersection, there are left- and right-turn bays on each of the two major-street approaches, left-turn bays on each of the minor-street approaches, and two through lanes on each approach. Two unsignalized access points exist between each signal.

The posted speed limit for the major street and the minor streets is 35 mi/h. The traffic signals operate in coordinated-actuated mode at a 100-s cycle. The offset for the eastbound through phase alternates between 0 and 50 s at successive intersections to provide good two-way progression.

The peak hour factor is 0.99, 0.92, 0.93, 0.94, 0.95, 0.96, and 0.97 at Intersections No. 1 through No. 7, respectively.

Analysis Replications

A Monte Carlo approach is used when there is some randomness in the value of a variable due to unknown influences and known influences by other variables that also have some randomness such that it is difficult to determine accurately the frequency (or probability) of the subject variable's value.

The urban street reliability method uses a Monte Carlo approach to generate variables describing weather events, incidents, and random demand fluctuations for each scenario in the reliability reporting period. One variation of this approach is to use an initial random number seed. The use of a seed number ensures that the same random number sequence is used each time a set of scenarios is generated for a given reliability reporting period. Any positive integer can be used as a seed value. Each set of scenarios is called a replication.

Because events (e.g., a storm, a crash) are generated randomly in the urban street method, highly unlikely events could be overrepresented or underrepresented in a given set of scenarios. To minimize any bias these rare events may cause, the set of scenarios should be replicated and evaluated two or more times. Each time the set of scenarios is created, the inputs should be identical, except that a different set of random number seeds is used. Then, the performance measures of interest from the evaluation of each set of scenarios are averaged to produce the final performance results.

Multiple analysis replications are needed to determine the confidence interval for the final performance results.

Five replications were found to provide sufficient precision in the predicted reliability measures for this example problem. The seed numbers in the following list were selected by the analyst for this example problem. The first replication used seed numbers 82, 11, and 63. The second replication used numbers 83, 12, and 64. This pattern continues for the other three replications.

- Weather event generator: 82, 83, 85, 87, 89
- Demand event generator: 11, 12, 14, 16, 18
- Incident event generator: 63, 64, 66, 68, 70

The random number sequence created by a specific seed number may be specific to the software implementation and computer platform used in the analysis. As a result, evaluating the same dataset and seed number in different software or on a different platform may result in results different from those shown here. Each result will be equally valid.

Computational Steps

This example problem proceeds through the following steps:

1. Establish the purpose, scope, and approach.
2. Code datasets.
3. Estimate weather events.
4. Estimate demand volumes.
5. Estimate incident events.
6. Generate scenarios.
7. Apply the Chapter 16 analysis method.
8. Conduct quality control and error checking.
9. Interpret results.

Step 1: Establish the Purpose, Scope, and Approach

Define the Purpose

The agency responsible for this urban street wishes to perform a reliability analysis of existing conditions to determine whether the facility is experiencing significant reliability problems. It also wants to diagnose the primary causes of any identified reliability problems on the facility so that an improvement strategy can be developed.

Define the Reliability Analysis Box

The results from a preliminary evaluation of the facility were used to define the general spatial and temporal boundaries of congestion on the facility under fair weather, nonincident conditions. All of the recurring congestion is encompassed by a study period consisting of the weekday morning peak period (7–10 a.m.) and a study area consisting of the 3-mi length of the facility between Intersections No. 1 and No. 7.

The reliability reporting period will include all weekdays, excluding major holidays, over the course of a year. The analysis period will be 15 min in duration.

Select Reliability Performance Measures

Reliability will be reported by using the following performance measures: mean TTI, 80th percentile TTI, 95th percentile TTI (PTI), reliability rating, and total delay (in vehicle hours) for the reliability reporting period.

Step 2: Code Datasets

Select Reliability Factors for Evaluation

The major causes of travel time reliability problems are demand surges, weather, and incidents. Reliability problems associated with work zones and special events were determined not to be key elements of the evaluation of this specific facility.

Code the Base Dataset

The base dataset was developed for the selected study section and study period. This dataset describes the traffic demand, geometry, and signal timing conditions for the intersections and segments on the subject urban street facility during the study period when no work zones are present and no special events occur. The data included in this dataset are described in Chapters 16 through 18.

Code the Alternative Datasets

Since no work zones are planned in the next year and no special events affect the facility on weekdays, only the base dataset will be required.

Step 3: Estimate Weather Events

This step predicts weather event date, time, type (i.e., rain or snow), and duration for each study period day in the reliability reporting period.

Identify Input Data

The default weather data for Lincoln, Nebraska, are a compilation of 10 years of historical data from NCDC (*8, 9*) and include the following statistics:

- Total normal precipitation,
- Total normal snowfall,
- Number of days with precipitation of 0.01 in. or more,

- Normal daily mean temperature, and
- Precipitation rate.

One inch of snowfall is estimated to have the water content of 0.1 in. of rain. Exhibit 36-61 shows the historical weather data for 2 months of the year.

Exhibit 36-61
Example Problem 6: Sample Weather Data for Lincoln, Nebraska

Weather Data	January	April
Normal precipitation[a] (in.)	0.67	2.90
Normal snowfall (in.)	6.60	1.50
Days with precipitation (days)	5	9
Daily mean temperature (°F)	22.40	51.20
Precipitation rate (in./h)	0.030	0.062

Note: [a] Rainfall plus water content of snow.

Determine Weather Events for Each Day

At this point in the analysis, weather is estimated for all days during a 2-year period. The analysis is not yet confined to the days within the reliability reporting period or the hours within the study period. The purpose of the extra calculations is to define the expected weather pattern for the study facility, which will be used in a later step to estimate incident frequencies.

A Monte Carlo approach is used to decide whether precipitation will occur in a given day. If precipitation occurs, then a Monte Carlo approach is also used to determine the type of precipitation (i.e., rain or snow), precipitation rate, total precipitation, and start time for the current day. The details of the process are described in the Urban Street Scenario Generation section of Chapter 37, Travel Time Reliability: Supplemental.

Exhibit 36-62 illustrates the results of the calculations for two nonholiday weeks in January and two nonholiday weeks in April. These results are based on the historical weather data for Lincoln, Nebraska, as shown in Exhibit 36-61. The random number values shown in the exhibit are intended to illustrate the computations within this specific table. Different values are obtained if the random number seed is changed. Only dates falling within the reliability reporting period are shown.

For reliability evaluation, total precipitation is assumed to be correlated perfectly with the precipitation rate so that storms producing a large total precipitation are associated with a high precipitation rate. This relationship is replicated by estimating both values by using the same random number.

As can be seen from Exhibit 36-62, the computed event durations may exceed 24 h, but when the end times are set for the event, any event that ends beyond 24:00 is truncated to 24:00.

Exhibit 36-62
Example Problem 6: Sample Generated Weather Events

Date	Precipitation RN R_D	Precipitation? (Yes/No)	Temperature RN RT_d	Mean Temperature (°F)	Snow/Rain?	Precipitation Rate RN RP_d	Precipitation Rate (in./h)	Total Precipitation RN RTP_d	Total Precipitation (in.)	Precipitation Start RN $RS_{d,m}$	Start of Precipitation Event	Precipitation Duration (h)	Time Wet After Precip. (h)	Day/Night?	Total Event Duration (h)	End of Precipitation	End of Wet Pavement
Jan 10	0.03	Yes	0.94	30	Snow	0.83	0.54	0.83	2.08	0.23	4:30	3.88	1.22	Night	5.10	8:23	9:36
Jan 11	0.00	Yes	0.22	19	Snow	0.62	0.29	0.62	0.27	0.21	4:45	0.95	1.28	Night	2.23	5:42	6:59
Jan 12	0.30	No															
Jan 13	0.90	No															
Jan 14	0.20	No															
Jan 24	0.00	Yes	0.89	28	Snow	0.09	0.03	0.09	0.01	0.12	3:00	0.01	1.23	Night	1.23	3:00	4:14
Jan 25	0.53	No															
Jan 26	0.45	No															
Jan 27	0.21	No															
Jan 28	0.60	No															
Apr 4	0.64	No															
Apr 5	0.24	Yes	0.11	45	Rain	0.40	0.03	0.40	0.02	1.00	23:15	0.68	0.07	Night	0.75	23:56	24:00
Apr 6	0.22	Yes	0.19	47	Rain	0.31	0.02	0.31	0.01	0.08	1:45	0.34	0.92	Night	1.26	2:05	3:00
Apr 7	0.78	No															
Apr 8	0.39	No															
Apr 11	0.55	No															
Apr 12	0.37	No															
Apr 13	0.10	Yes	0.28	48	Rain	0.82	0.11	0.82	0.54	0.39	7:15	5.05	0.72	Day	5.76	12:18	13:01
Apr 14	0.78	No															
Apr 15	0.27	Yes	0.98	61	Rain	0.73	0.08	0.73	0.30	0.57	11:30	3.62	0.66	Day	4.28	15:07	15:47

Note: RN = random number.

Determine Weather Events for Each Analysis Period

The days that have weather events are subsequently examined to determine whether the event occurs during the study period. Specifically, each analysis period is examined to determine whether it is associated with a weather event. An examination of the start and end times in Exhibit 36-62 indicates that the snow on January 10 and the rain on April 13 occur during the 7:00 to 10:00 a.m. study period.

Step 4: Estimate Demand Volumes

This step identifies the appropriate traffic volume adjustment factors (demand ratios) for each date and time during the reliability reporting period. These factors are used during the scenario file generation procedure to estimate the volume associated with each analysis period. If the analyst does not provide demand ratios based on local data, then the default ratios provided in Section 5, Applications, are used.

Identify Input Data

The input data needed for this step are identified in the following list.

- Hour-of-day demand ratio,
- Day-of-week demand ratio,
- Month-of-year demand ratio,
- Demand change factor for rain event, and
- Demand change factor for snow event.

The default values for these factors are obtained from Exhibit 36-27 to Exhibit 36-30. Their selection is based on the functional class of the subject facility, which is "urban principal arterial."

Determine Base Demand Ratio

First, the demand ratios for the day of the traffic count are determined. The count was taken on Tuesday, January 4, during the 7:00 a.m. hour. By using the default demand ratio data from Exhibit 36-27 through Exhibit 36-29, it can be seen that

- The hour-of-day ratio for the 7:00 a.m. hour for principal arterials is 0.071,
- The day-of-week ratio for Tuesdays is 0.98, and
- The month-of-year ratio for principal arterials in January is 0.831.

Multiplying these three factors together yields the base demand ratio of 0.0578. This ratio indicates that counted traffic volumes represent 5.78% of AADT, if this urban street's demand pattern is similar to that of the default demand data.

Determine Analysis Period Demand Ratio

A similar process is used to determine the demand ratio represented by each analysis period, except that an additional adjustment is made for weather. From Exhibit 36-30, a default 1.00 demand adjustment factor is applied to analysis periods with rain and a 0.80 adjustment factor is applied to analysis periods with snow.

As an example, the weather generator produced snow conditions for Monday, January 10, at 7:00 a.m. Default demand ratio data are obtained again from Exhibit 36-27 through Exhibit 36-29. The text accompanying Exhibit 36-30 states that a demand change factor of 0.80 is appropriate for snow conditions. Therefore, the factor values in the following list are established for the evaluation.

- The hour-of-day ratio for the 7:00 a.m. hour for principal arterials is 0.071,
- The day-of-week ratio for Mondays is 0.98,
- The month-of-year ratio for principal arterials in January is 0.831, and
- The demand change factor is 0.80.

Multiplying these factors together yields the demand ratio of 0.0463. This ratio indicates that the analysis period volumes represent 4.63% of AADT. Therefore, the traffic counts are multiplied by (0.0463 / 0.0578) = 0.800 to produce equivalent volumes for the hour starting at 7:00 a.m. on Monday, January 10.

Exhibit 36-63 shows a selection of demand profile computations for different hours, days, months, and weather events. Each row in this exhibit corresponds to one analysis period (i.e., scenario). Although the computations are performed for all nonholiday days of the year, this table illustrates the computations for selected days when dry weather or snow is predicted. The ratio shown in the last column of this exhibit is multiplied by the traffic counts for each signalized intersection to estimate the equivalent hourly flow rate for the associated analysis period.

Exhibit 36-63
Example Problem 6: Sample Demand Profile Calculations

Date	Weekday	Time	Weather	Weather Factor	Hour Factor	Day Factor	Month Factor	Total Factor	Total/Base
Jan 10	Mon	7:00	Snow	0.80	0.071	0.980	0.831	0.0463	0.800
Jan 10	Mon	7:15	Snow	0.80	0.071	0.980	0.831	0.0463	0.800
Jan 10	Mon	7:30	Snow	0.80	0.071	0.980	0.831	0.0463	0.800
Jan 10	Mon	7:45	Snow	0.80	0.071	0.980	0.831	0.0463	0.800
Jan 10	Mon	8:00	Snow	0.80	0.058	0.980	0.831	0.0378	0.654
Jan 10	Mon	8:15	Snow	0.80	0.058	0.980	0.831	0.0378	0.654
Jan 10	Mon	8:30	Dry	1.00	0.058	0.980	0.831	0.0472	0.817
Jan 10	Mon	8:45	Dry	1.00	0.058	0.980	0.831	0.0472	0.817
Jan 10	Mon	9:00	Dry	1.00	0.047	0.980	0.831	0.0383	0.662
Jan 10	Mon	9:15	Dry	1.00	0.047	0.980	0.831	0.0383	0.662
Jan 10	Mon	9:30	Dry	1.00	0.047	0.980	0.831	0.0383	0.662
Jan 10	Mon	9:45	Dry	1.00	0.047	0.980	0.831	0.0383	0.662
Apr 6	Wed	7:00	Dry	1.00	0.071	1.000	0.987	0.0701	1.212
Apr 6	Wed	7:15	Dry	1.00	0.071	1.000	0.987	0.0701	1.212
Apr 6	Wed	7:30	Dry	1.00	0.071	1.000	0.987	0.0701	1.212
Apr 6	Wed	7:45	Dry	1.00	0.071	1.000	0.987	0.0701	1.212
Apr 6	Wed	8:00	Dry	1.00	0.058	1.000	0.987	0.0572	0.990
Apr 6	Wed	8:15	Dry	1.00	0.058	1.000	0.987	0.0572	0.990
Apr 6	Wed	8:30	Dry	1.00	0.058	1.000	0.987	0.0572	0.990
Apr 6	Wed	8:45	Dry	1.00	0.058	1.000	0.987	0.0572	0.990
Apr 6	Wed	9:00	Dry	1.00	0.047	1.000	0.987	0.0464	0.802
Apr 6	Wed	9:15	Dry	1.00	0.047	1.000	0.987	0.0464	0.802
Apr 6	Wed	9:30	Dry	1.00	0.047	1.000	0.987	0.0464	0.802
Apr 6	Wed	9:45	Dry	1.00	0.047	1.000	0.987	0.0464	0.802

Step 5: Estimate Incident Events

The procedure described in this step is used to predict incident event dates, times, and durations. It also determines each incident event's type (i.e., crash or noncrash), severity level, and location on the facility. The procedure uses weather event and demand variation information from the two previous steps as part of the incident prediction process. Crash frequency data are used to estimate the frequency of both crash-related and non-crash-related incidents.

For an urban street reliability evaluation, incidents are categorized as being (*a*) segment-related or (*b*) intersection-related. These two categories are mutually exclusive.

Identify Input Data

Incident Frequency Data. Three-year average crash frequencies are determined from locally available crash records for each segment and intersection along the facility. These averages are shown in Exhibit 36-64. The frequency of noncrash incidents is estimated from the crash frequency data in a subsequent step. Noncrash incident frequency is not an input quantity due to the difficulty agencies have in acquiring noncrash incident data.

Exhibit 36-64
Example Problem 6: Locally Available Crash Frequency Data

Location	Crash Frequency (crashes/year)
Segment 1-2 (Intersections 1 to 2)	15
Segment 2-3 (Intersections 2 to 3)	16
Segment 3-4 (Intersections 3 to 4)	17
Segment 4-5 (Intersections 4 to 5)	18
Segment 5-6 (Intersections 5 to 6)	19
Segment 6-7 (Intersections 6 to 7)	20
Intersection 1	32
Intersection 2	33
Intersection 3	34
Intersection 4	35
Intersection 5	36
Intersection 6	37
Intersection 7	38

Work Zone and Special Event Crash Frequency Adjustment Factors. Work zones and special events are not being considered in this example; therefore, these crash frequency adjustment factors do not need to be provided.

Weather Event Crash Frequency Adjustment Factors. The default crash frequency adjustment factors given in Exhibit 36-31 are used.

Incident Duration Factors. The default incident detection and response times given in Exhibit 36-31 and the default clearance times given in Exhibit 36-32 are used.

Incident Distribution. The default incident distribution given in Exhibit 36-33 for urban street facilities with shoulders is used.

Compute Equivalent Crash Frequency for Weather

This step converts the average crash frequencies (supplied as input data) into the equivalent crash frequencies for each weather type.

First, the input crash frequency data for segments and intersections are converted into an equivalent crash frequency for each of the following weather conditions: clear and dry, rainfall, wet pavement (not raining), and snow or ice on pavement (not snowing). This conversion is based on the number of hours during a 2-year period that a particular weather condition occurs and the crash frequency adjustment factor corresponding to each weather condition. For this example problem, the number of hours in a year with a particular weather condition is determined from the default weather data for Lincoln, Nebraska.

This equation and the equations that follow are explained in Section 4, Urban Street Scenario Generation, in Chapter 37.

The equivalent crash frequency when every day is dry for street location *i* is computed with the following equation. Variable definitions are given in Exhibit 36-65.

$$FC_{str(i),\mathrm{dry}} = \frac{FC_{str(i)} 8{,}760 Ny}{Nh_{\mathrm{dry}} + CFAF_{rf} Nh_{rf} + CFAF_{wp} NH_{wp} + CFAF_{sf} NH_{sf} + CFAF_{sp} NH_{sp}}$$

$$Fc_{str(i),wea} = Fc_{str(i),\mathrm{dry}} CFAF_{wea}$$

Exhibit 36-65 illustrates the computations of the equivalent crash frequencies by weather type for two segments and three intersections. The calculations are similar for the other segments and intersections.

Exhibit 36-65
Example Problem 6: Computation of Crash Frequency by Weather Type

		Segments		Intersections		
Variable	**Definition**	**1-2**	**2-3**	**1**	**2**	**3**
$Fc_{str(i)}$	Observed average crash frequency	15	16	65	66	67
Ny	Number of years	2	2	2	2	2
Nh_{dry}	Hours of dry weather	17026.98	17026.98	17026.98	17026.98	17026.98
Nh_{rf}	Hours of rainfall	278.22	278.22	278.22	278.22	278.22
Nh_{wp}	Hours of wet pavement	104.33	104.33	104.33	104.33	104.33
Nh_{sf}	Hours of snowfall	64.61	64.61	64.61	64.61	64.61
Nh_{sp}	Hours of snow or ice on pavement	45.86	45.86	45.86	45.86	45.86
	Crash frequency adjustment factors for…					
$CFAF_{rf}$	Rainfall	2.0	2.0	2.0	2.0	2.0
$CFAF_{wp}$	Wet pavement	3.0	3.0	3.0	3.0	3.0
$CFAF_{sf}$	Snowfall	1.5	1.5	1.5	1.5	1.5
$CFAF_{sp}$	Snow or ice on pavement	2.75	2.75	2.75	2.75	2.75
	Calculated crash frequencies for…					
$Fc_{str(i),dry}$	Dry weather	14.50	15.47	30.94	31.91	32.88
$Fc_{str(i),rf}$	Rainfall	29.01	30.94	61.89	63.82	65.75
$Fc_{str(i),wp}$	Wet pavement	43.51	46.41	92.83	95.73	98.63
$Fc_{str(i),sf}$	Snowfall	21.76	23.21	46.41	47.86	49.32
$Fc_{str(i),sp}$	Snow or ice on pavement	39.89	42.54	85.09	87.75	90.41

Note: Hours of dry, rainfall, wet pavement, snowfall, and snow or ice on pavement sum to 17,520 h (2 years).

Establish Crash Adjustment Factors for Work Zones or Special Events

This step is skipped because work zones and special events are not being considered for this evaluation.

Determine Whether an Incident Occurs

This step goes through each of the 24 hours of each day that is represented in the reliability reporting period. For each hour, whether an incident occurs is determined. If an incident occurs, its duration is determined. Finally, for each incident identified in this manner, whether some portion (or all) of the incident occurs during a portion of the study period is determined.

Weather-Adjusted Incident Frequencies. First, for a given hour in a given day, the weather event data are checked to determine which weather condition (dry, rainfall, snowfall, wet pavement and not raining, or snow or ice on pavement and not snowing) was generated for that hour. The expected incident frequencies for street locations (i.e., segments and intersections) $Fi_{str(i),wea(h,d)}$ are determined from (*a*) the corresponding crash frequency for the given weather condition $Fc_{str(i),wea}$ (from a previous step) and (*b*) a factor $pc_{str,wea}$ relating total crashes to total incidents for the given weather condition (from the default values in the third column of Exhibit 36-33). If a special event or work zone was present on the given hour and day, the expected incident frequency is then multiplied by the segment or intersection (as appropriate) crash frequency adjustment factor $CFAF_{str}$ specified by the analyst for special events and work zones. The following equation is used:

$$Fi_{str(i),wea(h,d)} = CFAF_{str}\frac{Fc_{str(i),wea}}{pc_{str,wea}}$$

For example, weather was dry on Wednesday, April 6, at 9:00 a.m. For Segment 1-2, the equivalent crash frequency for dry weather is 14.50 crashes/year (from Exhibit 36-65). The ratio of crashes to incidents for segments in dry weather is 0.358. There is no work zone or special event, so the crash frequency adjustment factor is 1.0. Then

$$Fi_{seg1-2,\text{dry}} = (1.0)\frac{(14.50)}{(0.358)} = 40.5 \text{ incidents/year}$$

Similarly, snow was falling on Monday, January 10, at 7:00 a.m. The equivalent crash frequency for snowfall on Segment 1-2 is 21.76 crashes/year. The ratio of crashes to incidents for segments in snowy weather is 0.358. Therefore,

$$Fi_{seg1-2,sf} = (1.0)\frac{(21.76)}{(0.358)} = 60.8 \text{ incidents/year}$$

Conversion to Hourly Frequencies. Next, the incident frequency $Fi_{str(i),wea(h,d)}$ is converted to an hourly frequency $fi_{str(i),wea(h,d),h,d}$ by multiplying it by the percent of annual demand represented by the hour and by dividing by the number of days in a year (expressed as a ratio of hours). The same hour-of-day $f_{hod,h,d}$, day-of-week $f_{dow,d}$, and month-of-year $f_{moy,d}$ demand ratios used in Step 4 are used here. The following equation is used, where 8,760 is the number of hours in a year and 24 is the number of hours in a day.

$$fi_{str(i),wea(h,d),h,d} = \frac{Fi_{str(i),wea(h,d)}}{8{,}760}\left(24f_{hod,h,d}\right)f_{dow,d}f_{moy,d}$$

The month-of-year demand ratio for April is 0.987, the day-of-week demand ratio for Wednesday is 1.00, and the hour-of-day demand ratio for 9:00 a.m. is 0.047. The incident frequency for this day and time is calculated above as 40.5 incidents per year. Therefore, the equivalent hourly incident frequency for Segment 1-2 on Wednesday, April 6, at 9:00 a.m. is

$$fi_{seg1-2,\text{dry},0900,\text{Apr}06} = \frac{(40.5)}{(8{,}760)}(24 \times 0.047)(1.00)(0.987) = 0.00515 \text{ incident/h}$$

Similarly, the equivalent hourly incident frequency for Segment 1-2 on Monday, January 10, at 7:00 a.m. is

$$fi_{seg1-2,sf,0700,\text{Jan}10} = \frac{(60.8)}{(8{,}760)}(24 \times 0.071)(0.980)(0.831) = 0.00963 \text{ incident/h}$$

Probability of No Incidents. Incidents for a given day, street location, incident type, and hour of day are assumed to follow a Poisson distribution:

$$p0_{str(i),wea(h,d),con,lan,sev,h,d} = exp(-fi_{str(i),wea(h,d),h,d} \times pi_{str(i),wea(h,d),con,lan,sev})$$

where

$p0_{str(i),wea(h,d),con,lan,sev,h,d}$ = probability of no incident for a given combination of street location, weather condition, incident type, lane location, and severity for a given hour and day;

$fi_{str(i),wea(h,d),h,d}$ = expected hourly incident frequency for a given combination of street location and weather condition for a given hour and day (calculated above); and

$pi_{str(i),wea(h,d),con,lan,sev}$ = proportion of incidents for a given combination of street location, weather condition, incident type, lane location, and severity for a given hour and day (from the default values given in Exhibit 36-33).

Exhibit 36-66 demonstrates the determination of incidents for Segment 1-2 on April 6 for the 9:00 a.m. hour. Exhibit 36-67 does the same for January 10 for the 7:00 a.m. hour.

Exhibit 36-66
Example Problem 6: Incident Determination for April 6, 9:00 a.m., for Segment 1-2

Incident Type			Incident Proportion	Hourly Incident Frequency	exp (-*fi* × *pi*)	Random Number	Incident ?
Crash	1 lane	Fatal/injury	0.036	0.00515	0.99981	0.90019	No
Crash	1 lane	PDO	0.083	0.00515	0.99957	0.38078	No
Crash	2 lane	Fatal/injury	0.028	0.00515	0.99986	0.90860	No
Crash	2 lane	PDO	0.030	0.00515	0.99984	0.06081	No
Crash	Shoulder	Fatal/injury	0.021	0.00515	0.99990	0.82183	No
Crash	Shoulder	PDO	0.016	0.00515	0.99918	0.34916	No
Noncrash	1 lane	Breakdown	0.456	0.00515	0.99766	0.99900	Yes
Noncrash	1 lane	Other	0.089	0.00515	0.99954	0.59842	No
Noncrash	2 lane	Breakdown	0.059	0.00515	0.99970	0.69323	No
Noncrash	2 lane	Other	0.017	0.00515	0.99991	0.08131	No
Noncrash	Shoulder	Breakdown	0.014	0.00515	0.99993	0.13012	No
Noncrash	Shoulder	Other	0.007	0.00515	0.99996	0.44620	No

Notes: Incident proportions total 100%. PDO = property damage only.
Random numbers have been selected to illustrate this particular step of the computations. The same results would not necessarily be achieved in a full run of the procedure.

Exhibit 36-67
Example Problem 6: Incident Determination for January 10, 7:00 a.m., for Segment 1-2

Incident Type			Incident Proportion	Hourly Incident Frequency	exp (-*fi* × *pi*)	Random Number	Incident ?
Crash	1 lane	Fatal/injury	0.036	0.00963	0.99965	0.21041	No
Crash	1 lane	PDO	0.083	0.00963	0.99920	0.83017	No
Crash	2 lane	Fatal/injury	0.028	0.00963	0.99973	0.58437	No
Crash	2 lane	PDO	0.030	0.00963	0.99971	0.80487	No
Crash	Shoulder	Fatal/injury	0.021	0.00963	0.99981	0.35441	No
Crash	Shoulder	PDO	0.016	0.00963	0.99846	0.64888	No
Noncrash	1 lane	Breakdown	0.456	0.00963	0.99562	0.40513	No
Noncrash	1 lane	Other	0.089	0.00963	0.99914	0.98428	No
Noncrash	2 lane	Breakdown	0.059	0.00963	0.99943	0.61918	No
Noncrash	2 lane	Other	0.017	0.00963	0.99983	0.13712	No
Noncrash	Shoulder	Breakdown	0.014	0.00963	0.99987	0.30502	No
Noncrash	Shoulder	Other	0.007	0.00963	0.99993	0.33279	No

Notes: Incident proportions total 100%. PDO = property damage only.
Random numbers have been selected to illustrate this particular step of the computations. The same results would not necessarily be achieved in a full run of the procedure.

If more than one incident occurs at the same time and location, the more serious incident is considered in the methodology. During an incident, the methodology requires that at least one lane remain open in each direction of travel on a segment and on each intersection approach. If the number of lanes blocked by an incident is predicted to equal the number of lanes available on the segment or intersection approach, one lane is maintained open and the remaining lanes are blocked. For example, if the segment has two lanes in the subject travel direction and an incident occurs and is predicted to block two lanes, the incident is modeled as blocking only one lane.

Determine Incident Duration

If the result of the previous step indicates that an incident occurs in a given segment or intersection during a given hour and day, the incident duration is then determined randomly from a gamma distribution by using the average incident duration and the standard deviation of incident duration as inputs. These values are supplied as input data.

The duration is used in a subsequent step to determine which analysis periods are associated with an incident. The incident duration is rounded to the nearest quarter hour for 15-min analysis periods. The rounding is performed to ensure the most representative match between event duration and analysis period start and end times. This approach causes events that are shorter than one-half the analysis period duration to be ignored (i.e., they are not recognized in the scenario generation process).

Exhibit 36-66 shows that a noncrash, one-lane, breakdown incident was generated for Segment 1-2 on April 6 starting at the 9:00 a.m. hour. Exhibit 36-68 shows the inputs into the incident duration calculation and the result. As with other computations in this example problem involving random numbers, different values are obtained if the random number seed is changed.

Exhibit 36-68
Example Problem 6: Sample Calculation of Incident Duration

Variable	Value
Location	Segment 1-2
Incident type	Noncrash
Number of lanes involved	1
Incident severity	Breakdown
Weather	Dry
Incident detection time (min)	2.0
Incident response time, dry weather (min)	15.0
Incident clearance time (min)	10.8
Average incident duration (min)	27.8
Standard deviation of incident duration (min)	22.2
Average incident duration (h)	0.463
Standard deviation of incident duration (h)	0.371
Random number	0.57455
Gamma function alpha parameter (mean^2/variance)	1.5625
Gamma function beta parameter (variance/mean)	0.2965
Duration (h)	0.433
Rounded duration (nearest 15 min) (h)	0.50
Incident start time	9:00
Incident end time	9:30

Determine Incident Location

If an incident occurs at a segment or intersection during a given hour and day, its location is determined in this step. For intersections, the location is one of the intersection legs. For segments, the location is one of the two segment travel directions.

In the case of the incident identified on Segment 1-2 at 9:00 a.m. on April 6, the two directions of the segment have equal traffic volumes (see Exhibit 36-58) and therefore an equal probability of having the incident occur. This time, the scenario generator randomly assigned the incident to the westbound direction (identified as being associated with NEMA Phase 6 at the intersection).

Identify Analysis Period Incidents

The preceding steps of the incident estimation procedure are repeated for each hour of each day in the reliability reporting period. During this step, the analysis periods associated with an incident are identified. Specifically, each hour of the study period is examined to determine whether it coincides with an incident. If an incident occurs, its event type, lane location, severity, and street location are identified and recorded. Each subsequent analysis period coincident with the incident is also recorded.

Step 6: Generate Scenarios

This step uses the results from Steps 3 to 5 to create one scenario for each analysis period in the reliability reporting period. The base dataset coded in Step 2 represents the seed file from which the new scenarios are created.

As discussed previously, each analysis period is considered to be one scenario. There are 3,120 analysis periods in the reliability reporting period (= 4 analysis periods/hour × 3 hours/day × 5 days/week × 52 weeks/year × 1 year/reporting period). Thus, there are 3,120 scenarios.

Each scenario created in this step includes the appropriate adjustments to segment running speed and intersection saturation flow rate associated with the weather events or incidents that are predicted to occur during the corresponding analysis period. If an analysis period has an incident, the number of lanes is reduced, the saturation flow rate is adjusted for affected intersection lanes, and a free-flow speed adjustment factor is applied to the affected lanes in the segment. If an analysis period has rainfall, snowfall, wet pavement, or snow or ice on the pavement, the saturation flow rate is adjusted for all intersections, the free-flow speed is adjusted for all segments, and the left-turn critical headways are adjusted for all intersections.

The traffic demand volumes in each dataset are adjusted for monthly, weekly, and hourly variations.

Step 7: Apply the Chapter 16 Analysis Method

The analysis methodology for urban street facility evaluation is applied to each scenario generated in the previous step. This methodology is based on that described in Chapter 16. However, this methodology includes an additional procedure so that it can be used to evaluate segments that experience sustained spillback during the analysis period. At the conclusion of this step, the delay and queue length for each intersection, as well as the speed and travel time for each segment, are computed for each scenario.

Step 8: Conduct Quality Control and Error Checking

Because of the difficulty in the quality control of thousands of scenarios, it is recommended that the analyst focus on error checking and quality control on the base dataset. The results should be error-checked to the analyst's satisfaction to ensure that the dataset accurately represents real-world congestion on the facility under recurring demand conditions with no incidents and under dry weather conditions. The same criteria for error checking should be used as for a conventional HCM analysis, but with the recognition that any error in the base dataset will be crucial, because it will be reproduced thousands of times by the scenario generator.

The total delay for each scenario should be scanned to identify the study periods likely to be associated with exceptionally long queues. For a given study period, the final queue on each entry intersection approach for the last analysis period should not be longer than the corresponding initial queue for the first analysis period. The study period duration should be increased (i.e., started earlier, ended later) so that this condition is satisfied. Ideally, the study period is sufficiently long that these reference initial and final queues both equal zero. An efficient approach for making this check is to start by evaluating the scenario with the largest total delay.

Step 9: Interpret Results

This step examines the reliability results for the existing facility. The results are listed in Exhibit 36-69. Although the two travel directions have the same volume and capacity, several of the values in this exhibit vary slightly by travel direction because of the use of Monte Carlo methods.

Exhibit 36-69
Example Problem 6: Reliability Performance Measure Results

Measure	Eastbound	Westbound
Vehicle miles traveled[a]	2,260	2,257
Number of scenarios[a]	3,120	3,120
Base free-flow travel time[b] (s)	262.9	262.9
Mean TTI[b]	1.69	1.64
80th percentile TTI	1.57	1.56
95th percentile TTI (PTI)	2.98	2.61
Reliability rating (%)	93.2	94.1
Total delay[b] (veh-h)	72.0	

Notes: [a] This statistic represents a total for the reliability reporting period.
[b] This statistic represents an average of the value for each scenario (i.e., an average value for all scenarios).

VMT is computed for each scenario and added for all scenarios in the reliability reporting period. This statistic describes overall facility utilization for the reliability reporting period.

The travel time indices shown in Exhibit 36-69 were computed by finding the average (i.e., mean), 80th, and 95th percentile travel times for a given direction of travel across all scenarios and dividing by the facility's base free-flow speed. Since hourly demands, geometry, weather, and signal timings are identical in the two directions, the differences between the indices illustrate the effects of random variation in incidents and 15-min demands for the two directions.

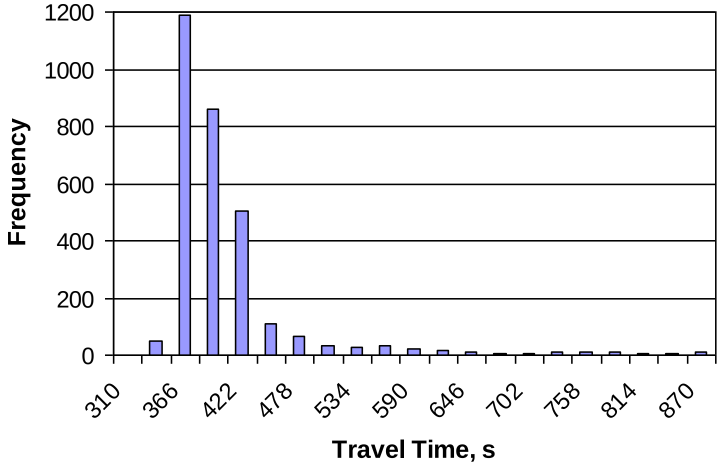
The reliability rating describes the percent of VMT on the facility associated with a TTI less than 2.5. A facility that satisfies this criterion during a given scenario is likely to provide LOS D or better for that scenario. The reliability ratings shown in the exhibit indicate that more than 90% of the VMT on the facility are associated with LOS D or better.

The total delay (in vehicle hours) combines the delay per vehicle and volume of all intersection lane groups at each intersection during a scenario. This statistic increases with an increase in volume or delay. It is the only statistic of those given in Exhibit 36-69 that considers the performance of all traffic movements (i.e., the other measures consider only the major-street through movement).

Hence, it is useful for quantifying the overall change in operation associated with a strategy. When it is considered on a scenario-by-scenario basis, this statistic can be used to identify scenarios with extensive queuing on one or more "entry" approaches (i.e., the cross-street intersection approaches and the major-street approaches that are external to the facility).

Exhibit 36-70 shows the travel time distribution for the facility's eastbound travel direction. That for the westbound direction has a similar shape. The longer travel times tend to be associated with poor weather. The longest travel times coincide with one or more incidents and poor weather.

Exhibit 36-70
Example Problem 6: Eastbound Travel Time Distribution



The reliability methodology was repeated several times to examine the variability in the reliability performance measures. Each replication used the same input data, with the exception that the three random numbers were changed for each replication. Exhibit 36-71 shows the predicted average and 95th percentile travel times for the eastbound travel direction based on five replications.

The last four rows of Exhibit 36-71 show the statistics for the sample of five observations. The 95th percentile confidence interval was computed by using Equation 36-7. The confidence interval for the average travel time is 432.2 to 441.1 s, which equates to ±1.36% of the overall average travel time. Similarly, the confidence interval for the 95th percentile travel time is ±3.16% of the average of the 95th percentile travel times. This confidence interval is larger than that of the average travel time because the 95th percentile travel time tends to be influenced more by the occurrence of incidents and poor weather. As suggested by the formulation of Equation 36-7, the confidence interval can be reduced in width by increasing the number of replications.

Exhibit 36-71
Example Problem 6: Confidence Interval Calculation for Eastbound Direction

Replication	Average Travel Time (s)	95th Percentile Travel Time (s)
1	443.7	783.8
2	441.4	787.5
3	432.8	758.4
4	439.3	740.0
5	433.7	772.9
Average	438.2	768.5
Standard deviation	4.79	19.6
95th percentile confidence interval	432.2–444.1 (±1.36%)	744.4–792.8 (±3.16%)

The contribution of demand, incidents, and weather to total VHD during the reliability reporting period is used to determine the relative contributions of each factor to the facility's reliability. The annual VHD takes into account both the severity of the event and its likelihood of occurrence. VHD is computed by identifying the appropriate category for each scenario and adding the estimated VHD for each scenario in this category. The results are summed for all scenarios in each category in the reliability reporting period. They are presented in Exhibit 36-72 and Exhibit 36-73. The categories have been condensed to facilitate the diagnosis of the primary causes of reliability problems on the urban street. Demand has been grouped into two levels. All foul weather and incident scenarios have been grouped into a single category each.

Exhibit 36-72
Example Problem 6: Annual VHD by Cause

	Total Delay by Demand and Weather (veh-h)				
	Low Demand		High Demand		
	Fair Weather	Foul Weather	Fair Weather	Foul Weather	Total
No incidents	52,957	6,337	120,393	5,025	184,713
Incidents	5,865	23	22,714	11,437	40,038
Total	58,822	6,360	143,107	16,462	224,751

Exhibit 36-73
Example Problem 6: Percentage of Annual VHD by Cause

	Low Demand		High Demand		
	Fair Weather	Foul Weather	Fair Weather	Foul Weather	Total
No incidents	23.6%	2.8%	53.6%	2.2%	82.2%
Incidents	2.6%	0.0%	10.1%	5.1%	17.8%
Total	26.2%	2.8%	63.7%	7.3%	100.0%

An examination of the cell values in Exhibit 36-73 yields the conclusion that the single most significant cause of annual delay in the urban street example is high demand, which accounts for 53.6% of annual delay during fair weather with no incidents. Incidents and bad weather collectively account for 22.9% of annual delay on the facility (17.8% + 7.3% + 2.8% – 5.1% – 0.0%).

EXAMPLE PROBLEM 7: URBAN STREET STRATEGY EVALUATION

Objective

This example problem illustrates an application of the reliability methodology for alternatives analysis. The objective is to demonstrate the utility of reliability information in evaluating improvement strategies. The strategies considered in this example involve changes in the urban street's geometric design or its signal operation. The changes are shown to affect traffic operation and safety, both of which can influence reliability.

Site

The same urban street described in Example Problem 6 is used in this example problem.

Required Input Data

The same types of required input data described in Example Problem 6 are used here. The conditions described in Example Problem 6 are used as the starting point for evaluating each of three strategies that have been identified as having the potential to improve facility reliability. One base dataset is used to describe the "existing" facility of Example Problem 6, while one base dataset is associated with each strategy, resulting in a total of four base datasets. Specific changes to the Example Problem 6 base dataset required to represent each strategy are described later. The three strategies are as follows:

1. Shift 5 s from the cross-street left-turn phase to the major-street through phase.
2. Change the major-street left-turn mode from protected-only to protected-permitted.
3. Eliminate major-street right-turn bays and add a second lane to major-street left-turn bays.

These strategies were formulated to address a capacity deficiency for the major-street through movements at each intersection. This deficiency was noted as part of the analysis described in Example Problem 6. The change associated with each strategy was implemented at each of the seven intersections on the street.

For this example problem, the changes needed to implement the strategies require changes only in the base datasets. However, some strategies may require changes in the reliability methodology input data, the HCM urban streets methodology input data, or both.

Computational Steps

This example problem proceeds through the following steps:

1. Establish the purpose, scope, and approach.
2. Code datasets.
3. Generate scenarios.
4. Apply the Chapter 16 analysis method.
5. Interpret results.

Step 1: Establish the Purpose, Scope, and Approach

Define the Purpose

The agency responsible for this urban street wishes to perform a reliability analysis of existing conditions to determine which of the three strategies offers the greatest potential for improvement in facility reliability.

Define the Reliability Analysis Box

The results from a preliminary evaluation of the facility were used to define the general spatial and temporal boundaries of congestion on the facility under fair weather, nonincident conditions. All of the recurring congestion is encompassed by a study period consisting of the weekday morning peak period (7–10 a.m.) and a study area consisting of the 3-mi length of facility between Intersections No. 1 and No. 7.

The reliability reporting period will include all weekdays, excluding major holidays, over the course of a year. The analysis period will be 15 min in duration.

Select Reliability Performance Measures

Reliability will be reported by using the following performance measures: mean TTI, 80th percentile TTI, 95th percentile TTI (PTI), reliability rating, and total delay (in vehicle hours) for the reliability reporting period.

Step 2: Code Datasets

Code the Base Dataset

The first base dataset represents existing conditions and is identical to the base dataset described in Example Problem 6. This base dataset was modified as follows to create a new base dataset (three in all) for each strategy being evaluated:

- The signal timing parameters for the Strategy 1 base dataset were modified at each intersection to reduce the phase splits for the minor-street left-turn movements by 5 s and to increase the phase splits for the major-street through movements by 5 s.
- The signal timing parameters for the Strategy 2 base dataset were modified at each intersection to change the major street left-turn mode from protected-only to protected-permitted. Furthermore, Chapter 12 of the HSM (*4*) indicates that intersection crash frequency increases by 11% on average when this change is made. Therefore, the crash frequency input data for each intersection were increased to reflect this change.
- The geometric parameters for the Strategy 3 base dataset were modified at each intersection to eliminate the major-street right-turn bays and to add a second lane to the major-street left-turn bays. Furthermore, Chapter 12 of the HSM (*4*) indicates that intersection crash frequency increases by 9% for this change. Therefore, the crash frequency input data for each intersection were increased to reflect this change.

Code the Alternative Datasets

Since no work zones are planned in the next year and no special events affect the facility on weekdays, only the base datasets will be required.

Step 3: Generate Scenarios

During this step, the reliability methodology is used to create one scenario for each analysis period in the reliability reporting period. The base datasets coded in Step 2 represent the seed files from which the scenarios associated with each strategy are created. As in Example Problem 6, one set of 3,120 scenarios is created for the existing facility. Additional sets of 3,120 scenarios are created for each of the three strategies.

Step 4: Apply the Chapter 16 Method

The analysis methodology for urban street facility evaluation is applied to each scenario generated in the previous step, as described in Example Problem 6.

Step 5: Interpret Results

This step examines the reliability results for the facility. Initially, the results for the existing facility are described. Then, the results for each of the three strategies are summarized and compared with those of the existing facility. The formulation of these strategies was motivated by an examination of the results for the existing facility. This examination indicated that the major-street through movements had inadequate capacity during the morning peak traffic hour for several high-volume months of the year.

Results for the Existing Facility

The results for the existing facility are the same as for Example Problem 6, given previously in Exhibit 36-69 through Exhibit 36-73.

Results for Strategy 1

In Strategy 1, 5 s are taken from the cross-street left-turn phase split. This change increases the time available to the major-street through (i.e., coordinated) phase and increases the through movement capacity. The results for this strategy are given in Exhibit 36-74. The first two rows list the average values obtained from five replications. The third row lists the change in the performance measure value. The last row indicates whether the change is statistically significant.

Exhibit 36-74
Example Problem 7: Results for Strategy 1

Case	Travel Time (s) Average	Travel Time (s) 95th Percentile	Total Delay (veh-h)	Reliability Rating (%)
Existing	438.2	768.5	70.7	93.2
Strategy 1	400.7	542.2	66.2	96.8
Change	–37.5	–226.3	–4.5	3.6
Significant?	Yes	Yes	Yes	Yes

Note: Results based on five replications.

The statistics in Exhibit 36-74 indicate that the strategy produces a relatively large improvement in travel time, particularly in the 95th percentile travel time. The strategy improves reliability during the peak hour for the high-volume months, which is reflected by the increase in the reliability rating. It forecasts an increase of 3.6% in the VMT for which LOS D or better is provided. On the other hand, delay to the cross-street left-turn movements increases, which partially offsets the decrease in delay to the major-street through movements. This trade-off is reflected by a small reduction of 4.5 veh-h total delay.

Results for Strategy 2

In Strategy 2, the major-street left-turn mode is changed from protected-only to protected-permitted. This change reduces the time required by the major-street left-turn phase, which increases the time available to the coordinated phase, and increases the through movement capacity. The results of the evaluation of this strategy are given in Exhibit 36-75.

Exhibit 36-75
Example Problem 7: Results for Strategy 2

Case	Travel Time (s) Average	Travel Time (s) 95th Percentile	Total Delay (veh-h)	Reliability Rating (%)
Existing	438.2	768.5	70.7	93.2
Strategy 2	382.9	473.5	49.6	97.3
Change	–55.3	–295.0	–21.1	4.1
Significant?	Yes	Yes	Yes	Yes

Note: Results based on five replications.

The statistics in Exhibit 36-75 indicate that the strategy produces a relatively large improvement in travel time, particularly in the average travel time. The strategy improves reliability during the peak hour for the high-volume months, reflected by the increase in the reliability rating. It forecasts an increase of 4.1% in the VMT for which LOS D or better is provided. The delay to the major-street through movements decreases without a significant increase in the delay to the other movements. This trend is reflected by the notable reduction of 21.1 veh-h total delay.

Results for Strategy 3

In Strategy 3, the major-street right-turn bays are eliminated and second lanes are added to the major-street left-turn bays. This change reduced the time required by the major-street left-turn phase, which increased the time available to the coordinated phase, and increased the through movement capacity. The results for this strategy are given in Exhibit 36-76.

Exhibit 36-76
Example Problem 7: Results for Strategy 3

Case	Travel Time (s) Average	Travel Time (s) 95th Percentile	Total Delay (veh-h)	Reliability Rating (%)
Existing	438.2	768.5	70.7	93.2
Strategy 3	410.0	460.2	59.0	98.5
Change	–28.2	–308.3	–11.7	5.3
Significant?	No	Yes	Yes	Yes

Note: Results based on five replications.

The statistics in Exhibit 36-76 indicate that the strategy produces a relatively large improvement in travel time, particularly in the 95th percentile travel time. The strategy improves reliability during the peak hour for the high-volume months, reflected by the increase in the reliability rating. It forecasts an increase of 5.3% in the VMT for which LOS D or better is provided. Delay to the major-street through movements decreases, as reflected by the reduction of 11.7 veh-h total delay. The change in average travel time is not statistically significant because the loss of the right-turn bays shifts the location of many incidents from the bays to the through lanes. This shift causes the average travel time for Strategy 3 to vary more widely among scenarios.

Summary of Findings

All three strategies improved the facility's reliability and overall operation. Strategy 1 (shift 5 s to the coordinated phase) provides some improvement in reliability of travel through the facility and some reduction in total delay in the system.

Strategy 2 (protected-only to protected-permitted) provides the *lowest average travel time* and the *lowest total delay.* It also provides a notable improvement in travel reliability.

Strategy 3 (eliminate right-turn lanes, increase left-turn lanes) provides the *biggest improvement in reliability* of travel. It also provides some overall benefit in terms of lower travel time and total delay.

The selection of the best strategy should take into consideration the change in road user costs, as measured in terms of reliability, total delay, and crash frequency. Viable strategies are those for which the reduction in road user costs exceeds the construction costs associated with strategy installation and maintenance.

7. REFERENCES

Some of these references are available in the Technical Reference Library in Volume 4.

1. Vandehey, M., W. Kittelson, P. Ryus, R. Dowling, J. Zegeer, N. Rouphail, B. Schroeder, A. Hajbabaie, B. Aghdashi, T. Chase, S. Sajjadi, R. Margiotta, J. Bonneson, and L. Elefteriadou. *Incorporation of Travel Time Reliability into the HCM.* SHRP 2 Project L08 Final Report. Kittelson & Associates, Inc., Portland, Ore., Aug. 2013.
2. Agarwal, M., T. H. Maze, and R. Souleyrette. *Impact of Weather on Urban Freeway Traffic Flow Characteristics and Facility Capacity*. Center for Transportation Research and Education, Iowa State University, Ames, Aug. 2005.
3. Weather Underground. *Weather History.* http://www.wunderground.com/history/. Accessed April 2012.
4. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
5. *A Policy on Geometric Design of Highways and Streets.* American Association of State Highway and Transportation Officials, Washington, D.C., 2011.
6. Habib, P. A. Transportation System Management Options for Downtown Curbside Pickup and Delivery of Freight. In *Transportation Research Record 758*, Transportation Research Board, National Research Council, Washington, D.C., 1980, pp. 63–69.
7. Cambridge Systematics, Inc., Texas A&M University, University of Washington, Dowling Associates, Street Smarts, H. Levinson, and H. Rakha. *Analytical Procedures for Determining the Impacts of Reliability Mitigation Strategies.* SHRP 2 Report S2-L03-RR-1. Transportation Research Board of the National Academies, Washington, D.C., 2013.
8. *Comparative Climatic Data for the United States Through 2010*. National Climatic Data Center, National Oceanic and Atmospheric Administration, Asheville, N.C., 2011. http://www.ncdc.noaa.gov. Accessed Sept. 21, 2011.
9. *Rainfall Frequency Atlas of the U.S.: Rainfall Event Statistics*. National Climatic Data Center, National Oceanic and Atmospheric Administration, Asheville, N.C., 2011. http://www.ncdc.noaa.gov/oa/documentlibrary/rainfall.html. Accessed Sept. 21, 2011.
10. Khattak, A., and N. Rouphail. *Incident Management Assistance Patrols: Assessment of Investment Benefits and Costs.* Report FHWA/NC/2005-02. North Carolina Department of Transportation, Raleigh, 2005.
11. Skabardonis, A., K. F. Petty, R. L. Bertini, P. P. Varaiya, H. Noeimi, and D. Rydzewski. I-880 Field Experiment: Analysis of Incident Data. In *Transportation Research Record 1603,* Transportation Research Board, National Research Council, Washington, D.C., 1997, pp. 72–79.

12. Jia, A., B. M. Williams, and N. M. Rouphail. Identification and Calibration of Site-Specific Stochastic Freeway Breakdown and Queue Discharge. In *Transportation Research Record: Journal of the Transportation Research Board, No. 2188*, Transportation Research Board of the National Academies, Washington, D.C., 2010, pp. 148–155.
13. Hallenbeck, M., M. Rice, B. Smith, C. Cornell-Martinez, and J. Wilkinson. *Vehicle Volume Distributions by Classification*. Report FHWA-PL-97-025. Chaparral Systems Corporation, Santa Fe, N.M., 1997.
14. Maki, P. Adverse Weather Traffic Signal Timing. Presented at 69th Annual Meeting of the Institute of Transportation Engineers, Las Vegas, Nev., 1999.
15. Park, B., T. K. Jones, and S. O. Griffin. *Traffic Analysis Toolbox Volume XI: Weather and Traffic Analysis, Modeling and Simulation*. Report FHWA-JPO-11-19. Federal Highway Administration, Washington, D.C., Dec. 2010. http://ntl.bts.gov/lib/37000/37800/37841/TAT%20Vol%20XI%20-%20508%20Files/tat_xi.pdf.