

Proposed Chapters for Incorporating Travel Time Reliability into the Highway Capacity Manual

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SHRP 2 Reliability Project L08

Proposed Chapters for Incorporating Travel Time Reliability into the Highway Capacity Manual



TRANSPORTATION RESEARCH BOARD
OF THE NATIONAL ACADEMIES

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Foreword

William Hyman, *SHRP 2 Senior Program Officer, Reliability*

This document contains two proposed chapters for the Transportation Research Board's *Highway Capacity Manual* (HCM) that introduce the concept of travel time reliability and offer new analytic methods. The chapters were prepared under SHRP 2 Project L08, Incorporation of Travel Time Reliability into the *Highway Capacity Manual*, but they have not been officially accepted by the Highway Capacity and Quality of Service (HCQS) Committee of the Transportation Research Board. The HCQS Committee has responsibility for approving the content of the HCM.

The scope of work for SHRP 2 Reliability Project L08 called for revising the methodologies for freeway facilities and urban streets. This research has resulted in a prospective Chapter 36 for the HCM concerning freeway facilities and urban streets and a prospective supplemental Chapter 37 that elaborates on the methodologies and provides an example calculation. In addition, a report documenting the research effort was prepared. It includes the user's guides for the computational engines for freeways and urban streets.

As with all SHRP 2 research, it is standard procedure to publish the key documents that result from each research project. The National Academies have approved Chapters 36 and 37 and the final report for publication as SHRP 2 products. The HCQS Committee, responsible for approval of changes to the HCM, has begun considering this material.

Proposed Chapters 36 and 37 set out methodologies for incorporating reliability into the HCM analytic procedures for freeway facilities and urban streets. The approach is to generate many freeway and urban street scenarios involving various causes of nonrecurring congestion, such as incidents, weather, and work zones, and use the scenarios as input to a computational engine to calculate travel time

over a segment. The travel times for each scenario are used to construct a distribution of travel time from which reliability performance measures can be derived.

Chapter 37 supplements Chapter 36. It provides reliability values for selected U.S. facilities, offers an alternative freeway incident prediction method, elaborates on the freeway and urban street scenario generators, explains how to measure reliability in the field, and gives an example problem.

CHAPTER 36

TRAVEL TIME RELIABILITY

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1. INTRODUCTION

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

- *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 (for longer-duration work) may also 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 to the facility's geometry or traffic control.

There are two widely held ways that the same underlying distribution of travel times can be characterized. Each is valid and leads to a set of performance measures that capture the nature of travel time variability. They are:

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.
2. Measures of the reliability of facility travel times, such as the number of trips that *fail or succeed* in accordance with a pre-determined performance standard, as expressed through metrics such as on-time performance or percent failure based on a target minimum speed or travel time.

For convenience, the remainder of this chapter uses the single term *reliability* to characterize both the variability-based and reliability-based approaches to characterizing the same facility 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.

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). Because this value is an average, there will be times of the day or days during the year when conditions are better than the average, due to lower-than-average traffic demands. There will also be days when conditions are much worse, due to incidents, severe weather, unusually high demand levels, or a combination of these.

Chapter 36, Travel Time Reliability, presents methods that can be used to describe *how often* particular operational conditions occur and *how bad* conditions

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

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 meeting a target travel time.

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

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.

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 devotes a number of pages to describing the reliability concept, how reliability can be measured, and how reliability can be applied to analyses to better 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 at a high level the travel time distribution estimation methods for freeway and urban street facilities, respectively. These descriptions omit many of the computational details. Readers wishing a greater level of detail about the methods are referred to Chapter 37, *Travel Time Reliability: Supplemental* for the computational details. 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 seven example problems illustrating the application of the reliability methods to a freeway facility and an urban street facility.
- Section 7 lists this chapter's references.

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 (e.g., 7 a.m. to 9 a.m. on non-holiday weekends).
- **Free-Flow Speed (urban streets).** The average running speed of through automobiles when traveling along a street under low-volume conditions and when not delayed by traffic control devices or other vehicles.

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

- **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 if traveling 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 scenario is 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 unique 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, this might be all non-holiday 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, 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 non-holiday weekday hours during the year). In addition, 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 otherwise affect traffic operations, thus affecting capacity;
- *Weather events* that affect capacity and possibly also demand;
- *Work zones* that close or restrict travel lanes, thus affecting capacity; and
- *Special events* that produce atypical traffic demands that may require managing by special traffic control measures.

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 desirably provided by the analyst when 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 due to an incident that occurs during the p.m. peak hour. A probability of occurrence is associated with each scenario, based either on 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.

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, etc. 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, etc. and creates a set of *scenarios* in which the base facility demand and capacity is adjusted to reflect the changes in demand and capacity that occur under each combination of conditions. Each scenario is then given to the *core HCM facility method*, which calculates the facility travel time associated with each scenario. The individual facility travel times are then

Input data beyond that 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 not available locally.

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, capacity, or both.

compiled into the facility's *travel time distribution*. This distribution can then be used to develop a variety of reliability and variability *performance measures* for the facility.

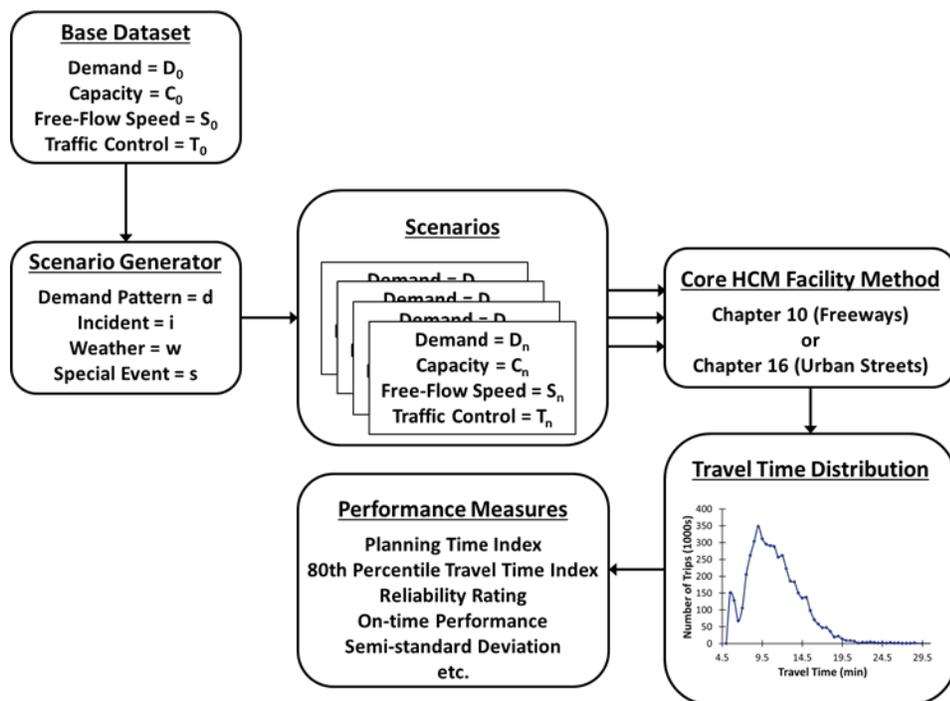


Exhibit 36-1
High-level Representation of
the Method for Estimating the
Travel Time Distribution

Because of the hundreds (or even thousands) of scenarios that are generated, this method is only practical to implement through the application of 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.

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 the 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 is 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

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

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; AADTs) or the demand measured on a specific day. This chapter's methods factor these demands based on 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. These datasets are called *alternative datasets*. The user must specify any changes to 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, then 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

Beyond the data normally needed for an HCM facility operations evaluation, additional data are required to perform a reliability evaluation on a facility. Exhibit 36-2 lists the general categories of data that are required by facility type. Specific 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 used.	Required when defaulted weather data 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 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).

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 p.m. to 6:00 p.m.). If oversaturated conditions occur during the study period, then at least the first analysis period should be undersaturated. The maximum study period duration is 24 h.

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. Additionally for urban streets, if the directional distribution of traffic volume changes significantly during the day, then separate study periods should be established for each time period where the directional distribution is relatively constant.

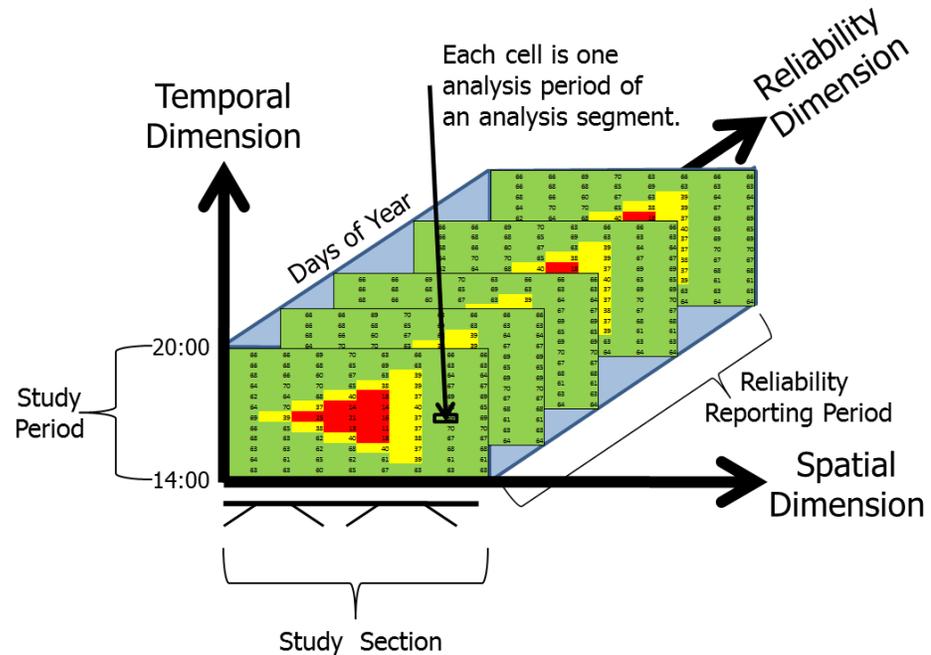
Reliability Reporting Period

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. It 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 fully describe the temporal representation of the performance measure (e.g., average travel time on non-holiday weekdays from 4:00 p.m. to 6:00 p.m. for the current year). Exhibit 36-3 presents the relationships between the analysis, study, and reliability reporting periods.

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

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

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.

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

- Hour-of-day factors for each hour of the study period (up to 24, but typically 6 or fewer in practice).
- Day-of-week factors for each day included as part of the reliability reporting period (up to 7).
- 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, respectively.

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

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.

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 based on the presence of weather conditions. The specific types of weather data used in the freeway and urban street methods are sufficiently different that they are described separately below.

Freeway Facilities

The freeway facility method requires the probabilities of occurrence of eleven 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 ten 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 that encompasses all other types of weather that have no or minimal impacts 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 ten severe weather events.

Weather Event	Definition
Medium rain	$>0.10 \leq 0.25$ in./h
Heavy rain	>0.25 in./h
Light snow	$>0 \leq 0.05$ in./h
Light-medium snow	$>0.05 \leq 0.10$ in./h
Medium-heavy snow	$>0.10 \leq 0.50$ in./h
Heavy snow	>0.50 in./h
Severe cold	$<-4^{\circ}\text{F}$
Low visibility	$<1 \geq 0.50$ mi
Very low visibility	$<0.50 \leq 0.25$ mi
Minimal visibility	<0.25 mi
Non-severe weather	All other conditions not listed above

Default values have been developed for the probability of occurrence, in each hour of each month, of the eleven types of weather events for 101 metropolitan areas in the U.S. based on data from 2001–2010. Default values have also been developed for the average durations of each type of severe weather event in each area (3). These defaults should be sufficient for most analyses; however, analysts are free to substitute more recent or more localized data when 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 ($^{\circ}\text{F}$), and
- Precipitation rate (in./h).

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.

Exhibit 36-4
Definitions of Freeway Facility
Weather Events

The default weather data should be sufficient for most analyses.

Default values are available for each of these statistics for 284 locations in the U.S. based on data from 2001–2010. These defaults should be sufficient for most analyses; however, analysts are free to substitute more recent or more localized data when 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 snow pack (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. When possible, an appropriate local value should be established for the subject facility. If not possible, Section 5, Applications, provides a default value for this input 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 specific 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, representing the fraction of time during the study period in each month where a given incident type occurs. Incident types are defined as: no incident, shoulder closure, one lane closures, two lane closures, etc., 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 segment(s)*, which are defined by the analyst. Up to three incident segments can be defined along the facility, which are ideally located towards the beginning, in the middle, and towards 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.

For situations where 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 for use when this alternative approach is used to estimate the facility incident rate. The effects of treatments to improve facility safety, incident duration, or both can also be evaluated using this alternative approach, but it should be recognized that the method's predicted changes in reliability will be based on changes from national average conditions rather than on local conditions.

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.

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 downstream intersection stop bar). For the purposes of reliability analysis, it is necessary to modify this definition for the exclusive purpose of classifying collision data by segment or intersection location. For collision data purposes, the classification of whether or not a collision occurred at the intersection or on the segment is determined using the definitions given in *Highway Safety Manual* 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 non-crash incident frequency, type, and location because most agencies do not have detailed non-crash 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. These crash frequencies represent 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 one 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 due to diversion, while changes to 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 ($= 2.0 \times 0.5$). 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, while clearance times are also dependent on the incident severity and location (e.g., shoulder vs. 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 non-crash), lane location (shoulder, one lane, two or more lanes), severity (fatal/injury or PDO), and weather condition (dry, rainfall, wet pavement, snowfall or snow/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 possible 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 non-crash incidents by street location (segment or intersection) (4 total values; proportions should total 1.000 for a given street location);
- Proportion of shoulder, 1 lane, and 2+ lane incidents by street location and event type (crash or non-crash) (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;

- Proportion of breakdown and other non-crash 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 that exist 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 are 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. This distribution is modified accordingly when shoulders are not present on the subject facility. For a shoulder to be considered “present,” it must be sufficiently wide that it can store a disabled vehicle (such 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 its occupancy during the study period is sufficient to preclude its use as a refuge for disabled vehicles. It is judged that the proportion of on-street parking occupied would need to be less than 30% to provide reasonable assurance that there will be opportunity to move a disabled vehicle from the through lanes to an open stall.

Traffic Counts

Both the freeway and 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 to know what the base dataset demand represents.

The freeway facility method requires a *demand multiplier*. If the supplied demand patterns are relative to AADT, then 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, then 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 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 comprise the reliability reporting period. Specifically, it is used to determine the appropriate traffic volume adjustment factors for each scenario. The functional classes that are considered are:

- 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 through trips that are entering, leaving, or passing 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. These 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 16–18, 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 currently not accounted for in the methodology. In addition, a given weather event (e.g., rain, snow) is always assumed to occur at its mean duration value. Further, 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, which are the 25th, 50th, and 75th percentiles of the incident duration distribution.
- The methodology does not include the effect of managed lanes on reliability, as the HCM freeway facility method currently 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 that occur on some streets and influence their operation, including:

- Truck pick-up 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 pick-up-and-delivery activities in downtown urban areas can be considered incident-like 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 mid-segment 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 that can extend 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 safely clear the tracks. Signal coordination may be disrupted for several cycles following 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

As travel time reliability methods are new to the HCM, reliability concepts do not appear in Volume 1. Therefore, this section summarizes key reliability concepts, including discussing why an analyst might want to evaluate a facility's reliability, presenting suggested performance measures and typical values for some common measures, identifying potential data sources for a reliability analysis, and interpreting the results of a reliability analysis.

OBJECTIVES FOR RELIABILITY ANALYSIS

An important first step in any analysis is defining why the analysis is being performed, including defining the key questions or issues, identifying performance measures that help answer those questions, and establishing a basis of comparison for interpreting the analysis results. Reliability analysis is no different. Examples of potential objectives of a reliability analysis include:

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

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 (LRTPs), transportation improvement programs (TIPs), corridor or area-wide plans, major investment studies, congestion management, operations planning, and demand forecasting. The Use Cases portion of Section 5, Applications, describes these potential applications in greater detail.

PERFORMANCE MEASURES

The reliability methodology produces two types of performance measures:

1. Distributions of the performance measures produced by the HCM facility methodologies.
2. 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. These 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.

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

Performance Measures Derived from the Travel Time Distribution

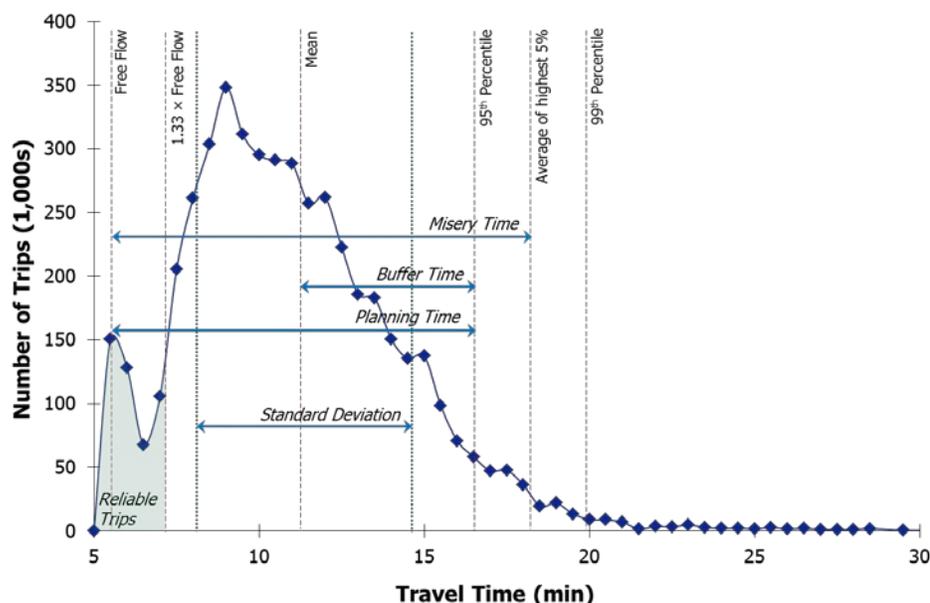
The travel time distribution can be used to derive a variety of performance measures that describe different aspects of reliability. These include:

- *Percentile-based measures*, such as the 95th percentile travel time;
- *On-time measures*, such as the percent of trips completed within a defined travel time threshold;
- *Failure measures*, such as the percent 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. Some of these measures include:

- *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 to 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 indexes 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 *travel time index (TTI)*, which is the ratio of the actual travel time on a facility to the theoretical travel time if traveling at free-flow speed. When used to describe

the travel time distribution, TTIs are often given as a stated 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 *planning time index (PTI)*.

Analysts can also define a *policy index*, which is similar to the TTI, but replaces free-flow speed with a target speed for the facility. This target speed can represent a desired minimum operating speed for the facility (typically chosen as a speed just above breakdown), or can represent 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 different aspects of the travel time reliability distribution. The following performance measures 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:

- *Travel time* (minutes). Travel time is a versatile measure, as it can be monitored over time (for trend analysis), monetized (when 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 to each other (e.g., for project prioritization purposes, or to compare individual facility results to 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 due to the influence of rare, very long travel times in the distribution.
- *Annual delay* (veh-h and p-h). Annual delay represents the average vehicle- or person-hours of travel (VHT, PHT) that occurs minus that which would occur under free-flow conditions. Delay is useful because economic analyses have a long history of monetizing delay.

Measures Describing Unreliability

When one measures or predicts travel times over a long period of time (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:

- *Planning time index* (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 (4), which makes it useful for comparison and prioritization purposes.
- *Failure/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 compared to urban streets, as 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 the most 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, the reliability rating is recommended to be reported 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 it is unknown whether a larger database would produce similar percentile values. Although the table is intended as an aid to analysts in comparing a given facility's performance to that of other U.S. facilities, caution is needed when

comparing a facility's operation to that of those shown in these exhibits, as the analyst's facility may have different characteristics than the sample of facilities.

These data are derived from field measurements. Note that the urban street values of TTI and PTI are calculated 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.

As an example of how to read Exhibit 36-6, assume that one has a measured PTI for a freeway for the a.m. peak period. 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, while only 5% of them had PTIs greater than 3.92 (i.e., 95% had PTIs less than 3.92).

Percentile Rank	Freeways			Urban Streets		
	TTI	Mean TTI	PTI	TTI	Mean TTI	PTI
AM 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
PM 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.

Note: 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.

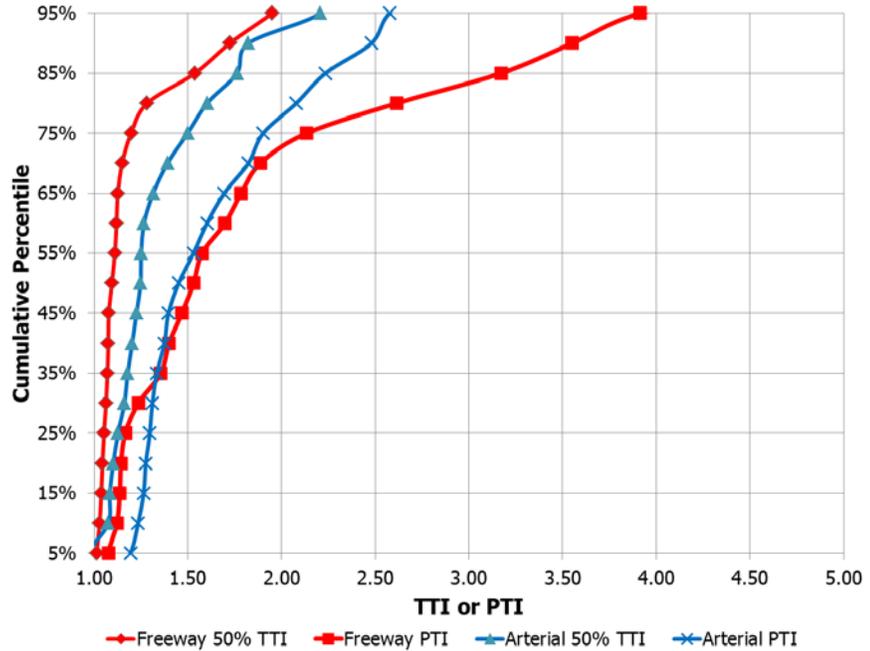
Exhibit 36-7 through Exhibit 36-9 illustrate the distribution of TTI and PTI from the sample of freeways and urban streets. It can be seen from this exhibit that a greater range of unreliable conditions is observed on freeways, compared to urban streets, as measured by the spread between the most reliable and least reliable facilities included in the dataset.

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.

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

Exhibit 36-7

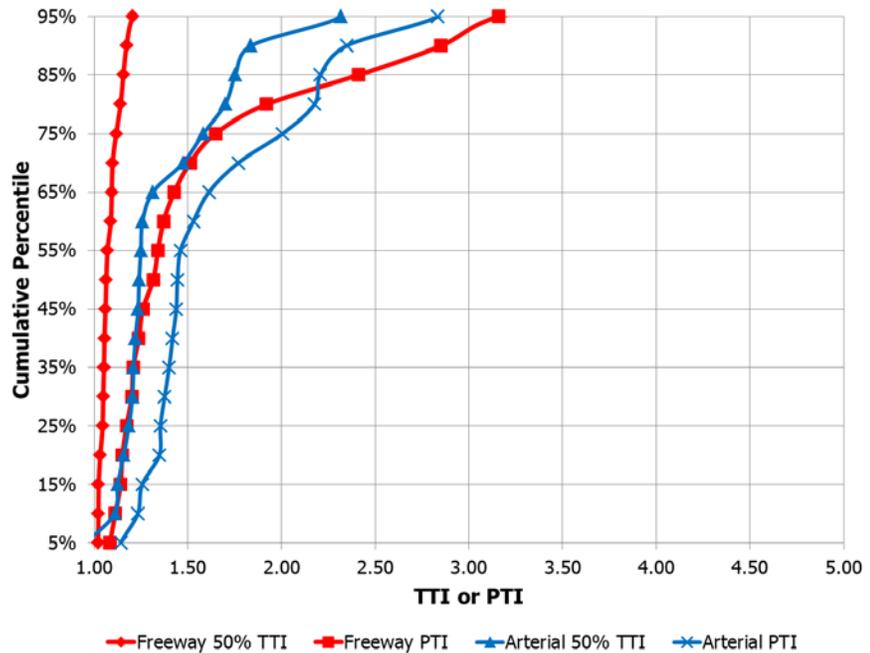
TTI and PTI Distribution on U.S. Freeways and Urban Streets (AM Peak Period)



Note: 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)



Note: 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.

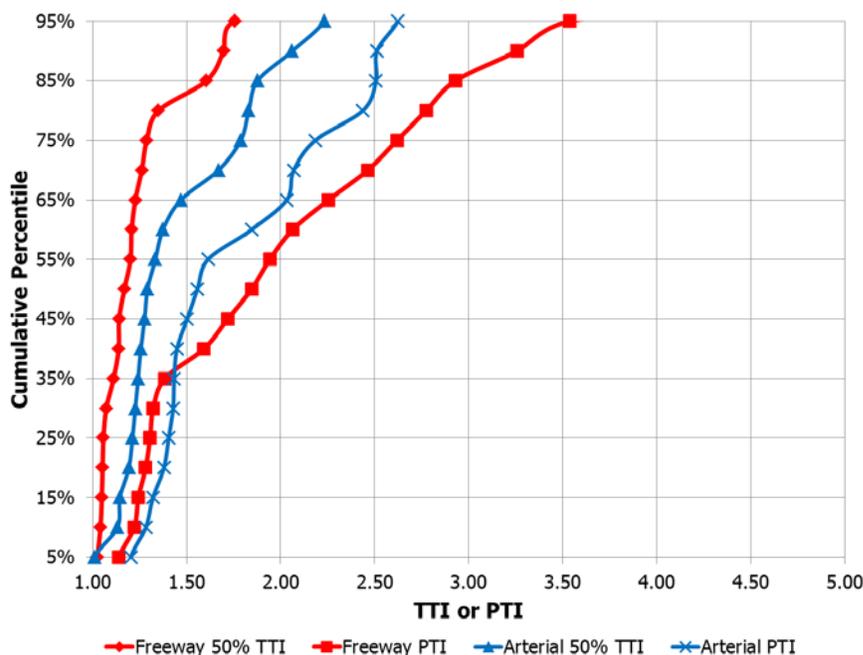


Exhibit 36-9
TTI and PTI Distribution on
U.S. Freeways and Urban
Streets (PM Peak Period)

Note: 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 from 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 amount of volume that reaches 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 (7) and average precipitation rate data in the Rainfall Frequency Atlas (8). The more

detailed hourly weather data needed for a freeway facility analysis is 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. It should be kept in mind that a 10-year weather dataset is desirable, to capture rare but highly impactful weather events.

Finally, analysts should consider the location of the facility relative to the weather station, because elevation differences, proximity to large bodies of water, and other factors that create microclimates may result in certain types of weather events (e.g., snow, fog) occurring with significantly different probabilities on the facility than 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 very 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 (9, 10). Details of the process are described in Chapter 37, *Travel Time Reliability: Supplemental*.

Urban Streets

The expected crash frequency can be computed using the predictive method in Chapter 12 of the 2010 *Highway Safety Manual (HSM)* (4). If this method cannot be used, then a three-year crash history for the subject segment or intersection can be used to estimate its expected crash frequency. 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 there were 15 crashes reported during a recent three-year period and 5 of these crashes occurred during a six-month period when a work zone was present, then the expected crash frequency is estimated as 4.0 crashes per year ($= [15 - 5]/[3 - 0.5]$). A technique for determining whether a crash is a segment- or intersection-related crash is described in Appendix A to Part C of the 2010 *HSM* (4).

Work Zones

A schedule of long-term work zones should be obtained from the roadway operating agency, indicating the days and times when the work zone will be in effect and the portions of the roadway that will be affected. 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 points in time will need to be provided as separate alternative datasets. When available, detailed traffic control plans for each work zone 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 of time. 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 against a rival, compared to 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. However, 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 very individual choice that each agency must make between unachievable perfection and achievable performance. 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 ultimately up to the agency.

Criterion #1: How Does Reliability Compare to 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, this information can be used to either modify the computation of the reliability statistics, or the reliability statistics can be translated into delays so that failures to meet agency policy can be more quickly identified.

Equation 36-1

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. It is then relatively easy to determine the extent to which the facility meets the agency's target performance level by comparing the computed reliability statistic to the target value of 1.00. 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.

$$TTI(\text{policy}) = \frac{\text{mean travel time}}{\text{policy travel time}}$$

$$PTI(\text{policy}) = \frac{95\text{th percentile travel time}}{\text{policy travel time}}$$

where

- *TTI (policy)* = travel time index, based on the agency's policy (or target) travel time for the facility (unitless);
- *PTI (policy)* = planning time index, based on the agency's 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, then the policy travel times are computed 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 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 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), then the *TTI* and *PTI* can be readily converted into equivalent delay estimates for the facility and compared to the agency standard.

$$\begin{aligned}\text{Average Delay Per Trip} &= 3,600 \times \frac{\text{Length}}{\text{FFS}} \times (TTI - 1) \\ \text{Average Delay Per Mile} &= 3,600 \times \frac{1}{\text{FFS}} \times (TTI - 1) \\ \text{Average Delay Per Signal} &= 3,600 \times \frac{\text{Length}}{\text{NS} \times \text{FFS}} \times (TTI - 1)\end{aligned}$$

Equation 36-2

where *average delay* is the average delay per vehicle in seconds and

TTI = Travel time index, the mean travel time divided by the free-flow travel time for the facility (unitless);

PTI = Planning time index, the 95th percentile 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).

For the 95th percentile delay per trip, per mile, and per signal, substitute PTI for TTI in Equation 36-2. These equations can be solved for TTI or PTI to determine the maximum acceptable values of these indices consistent with the agency's maximum delay policy.

Criterion #2: How Does Reliability Compare to 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 that 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, then their TTI goals for their freeways would be 1.97 or less and 1.53 or less for urban streets. Their PTI goals for acceptable reliability would be less than 3.60 for freeways and 1.94 for urban streets.

Criterion #3: How Does Reliability Compare to HCM Level of Service?

This criterion involves translating reliability results into more traditional HCM level of service results that decision-makers may be more comfortable with. This involves using the reliability results to identify what percent of time a facility is operating at an unacceptable LOS and determining a percentage of time that is unacceptable.

For example, the agency's LOS 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 are high to eliminate the 5% risk.

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 which 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 to the values in Exhibit 10-7 to determine if 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 to the urban street LOS criteria in Exhibit 16-4 to determine if 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, they 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, different logical approaches may be taken for assigning the proportional responsibility to individual causes when more than one is acting in combination.

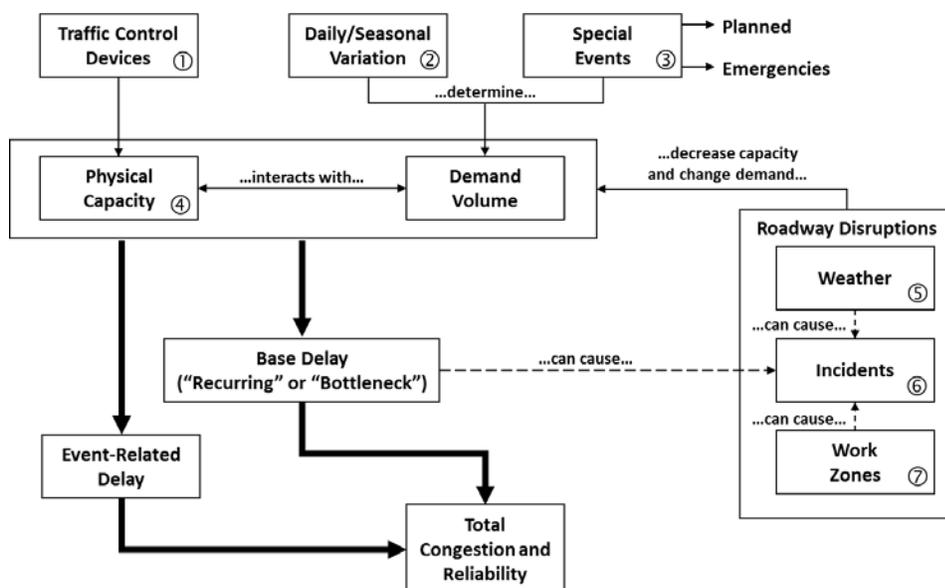


Exhibit 36-10
Interrelationship Between Causes of Congestion and the Facility

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.

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

Incidents	Low Demand		Moderate Demand		High Demand		Total
	Fair Weather	Bad Weather	Fair Weather	Bad Weather	Fair Weather	Bad Weather	
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%)	1,328 (5%)
3 lanes closed	621 (2%)	40 (<1%)	468 (2%)	23 (<1%)	1,510 (6%)	32 (<1%)	2,694 (10%)
Total	3,774 (14%)	551 (2%)	3,572 (13%)	456 (2%)	17,759 (65%)	1,124 (4%)	27,236 (100%)

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).

Diagnosing Primary Causes of Unreliability

The diagnosis proceeds by first examining the cells of the matrix to identify the cells 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 see if 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.

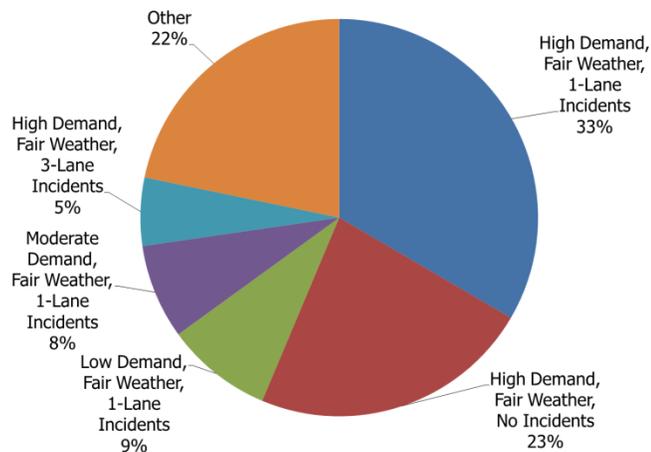


Exhibit 36-12
Example Pie Chart of
Congestion Causes

Develop 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 on the facility show high potential for improving reliability on the facility; and
- Measures to manage incidents that close a single lane show high potential for improving reliability.

The diagnostic process also reveals that in this particular example, bad weather and extreme incidents (2+ lane closures), although severe when they happen, are infrequent enough to be minor contributors to total annual delay on the example 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.

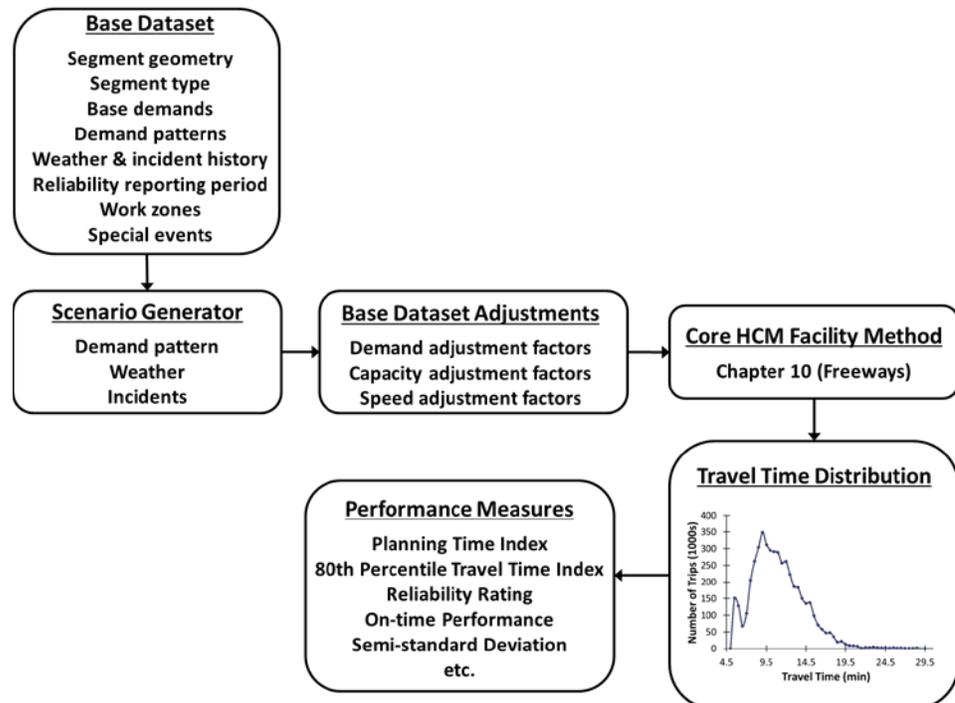
The freeway methodology is computationally intense and requires software to implement. This intensity stems from the need to create and process the input and output data associated with the hundreds to thousands of scenarios considered for a typical reliability reporting period. Due to the intensity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

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. These 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 not available locally, but the analyst is encouraged to supply facility-specific data whenever 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, different combinations of 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—thus reducing analysis time—without significantly impacting 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 based on 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 based on 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 the above 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 using 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:

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).
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, as 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 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 analysis periods comprising a given scenario's study period. (Continuing 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 together to reduce the total number of scenarios that will be generated and calculated (thus reducing 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 twelve 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, 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, based on national data shown in Exhibit 36-14 (4), 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.

Month	Day of Week						
	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. (17).

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

Weather Event Generation

Weather events are generated based on their probability of occurrence during a given month (or set of months, if months were aggregated during the traffic demand variability process). As shown previously in Exhibit 36-4, the method incorporates ten 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 which 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 (FFS) 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 FFS; 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: Kittelson & Associates et al. (7).

Notes: CAF = capacity adjustment factor, SAF = free-flow speed adjustment factor.

As described previously 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, thus generating a maximum of 11 weather events \times 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

Incidents are generated based on their probability of occurrence in a given month. As described previously 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 \times 3 durations \times 3 locations \times 5 incident severities = 90 patterns with an incident. There is also 1 “no incident” pattern, resulting in 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 2-lane closure incident on a 6-lane directional facility results in a loss of two full lane capacities, in addition to

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 than the time to clear the incident. Incident severity reflects the maximum number of lanes blocked.

maintaining only 75% of the remaining four open lanes' capacities. The end 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 previously in the Incident Data subsection of Section 1, Introduction, full-facility closures are not modeled.

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 also be provided. Capacity effects of work zones are taken primarily from the existing literature, including the HCM. Exhibit 36-17 shows example CAFs computed from Exhibit 10-14. Exhibit 36-17 assumes a work-zone FFS 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, as those are highly facility- and event-specific.

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, assuming a work zone FFS of 55 mi/h.

Note: 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 non-recurring congestion events are independent of each other. There is very little supporting empirical data that enable 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 non-recurring events will occur. An upper bound on the number of scenarios can be estimated, however. Neglecting the presence of work zones and special

Exhibit 36-16
Incident Effects on Capacity

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

events, and assuming 12 demand pattern scenarios, 22 weather scenarios, and 91 incident scenarios, it is possible to generate up to 24,000 scenarios 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
Generated by the Scenario
Generator

Scenario Number	De-mand Pattern	Scenario Probability	Weather		Incident				Incident Duration	Weather Duration
			Event Type	Start Time	Type	Duration	Start Time	Segment		
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

Note: N/A = not applicable, SP = study period.

FACILITY EVALUATION

Evaluation Process

Each scenario produced by the scenario generator is analyzed 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. Those 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 facility-wide 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 FFS with an adjusted FFS incorporating the appropriate SAF for the prevailing weather conditions.

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

Equation 36-6

where

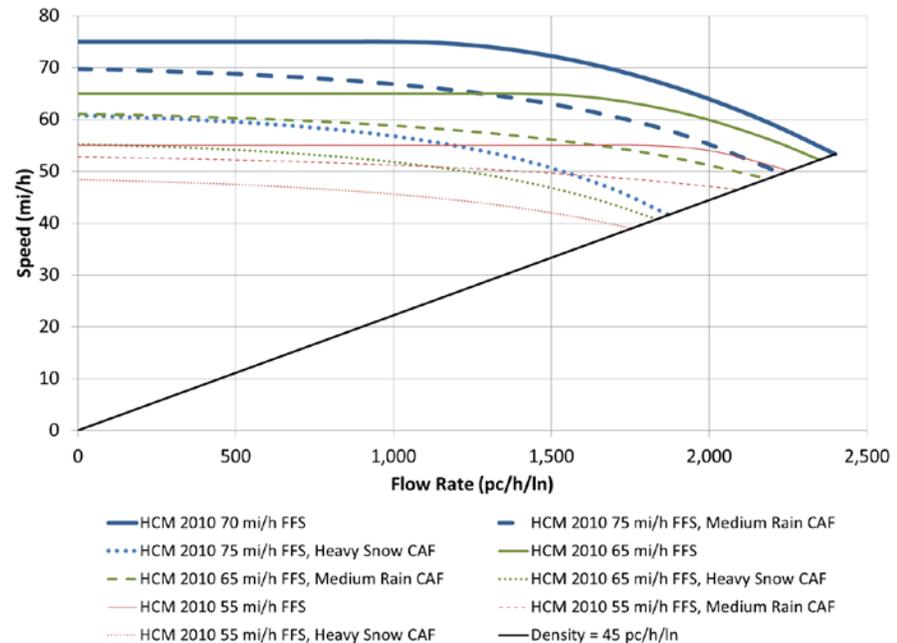
- S = segment speed (mi/h),
- FFS = segment free-flow speed (mi/h),
- SAF = speed adjustment factor,
- C = original segment capacity (pc/h/ln),
- CAF = capacity adjustment factor, and
- v_p = segment flow rate (pc/h/ln).

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 FFS and by extension, the estimated segment speed. Whenever the Chapter 12 or Chapter 13 methodology uses capacity or FFS, the freeway reliability methodology replaces them with (capacity \times CAF) and (FFS \times SAF), respectively.

Exhibit 36-19

Example Speed–Flow Curves
for Basic Freeway Segments
After CAF and SAF
Adjustments



Note: FFS = free-flow speed, CAF = crash adjustment factor.

Queue-Discharge Flow Rate

To more realistically model queue propagation and dissipation on congested freeway facilities, 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 have a significant effect on the duration and severity of congestion. This 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 very severe congestion when a combination of high demand, severe weather, and incidents occur. Some cases (e.g., multiple interacting bottlenecks) may be beyond the ability of a macroscopic model to analyze. In addition to providing warning flags for such occurrences, the method incorporates additional performance measures to monitor those effects, including:

- Total number of vehicles denied entry onto the facility when the first segment is fully queued,
- 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 across. These measures include:

- *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 (8 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 using various performance measures, including:

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

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

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.

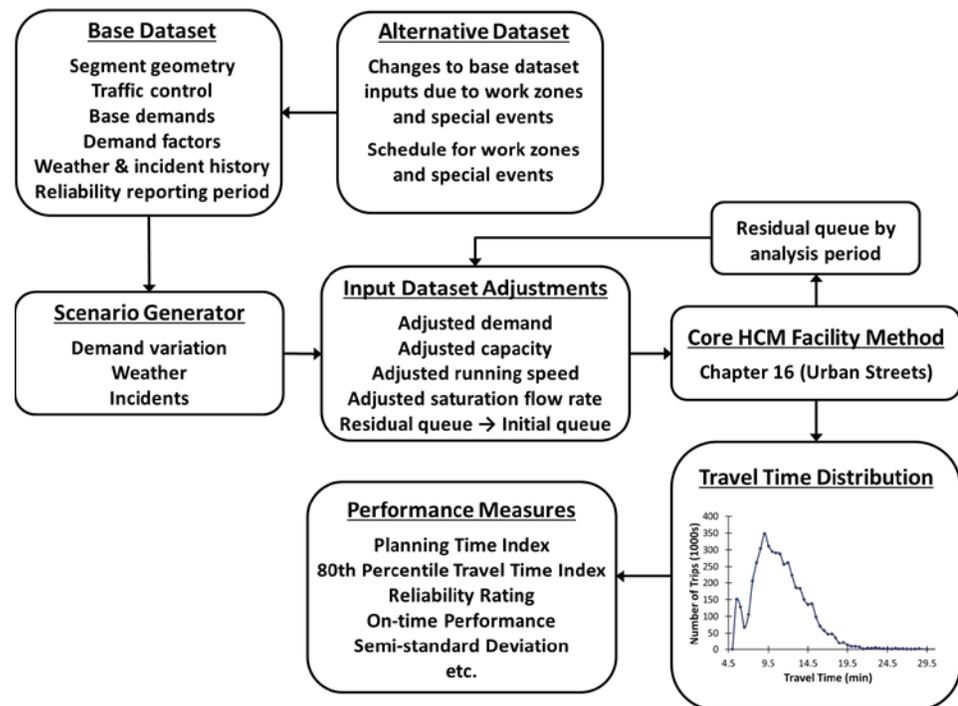
The urban street reliability methodology is computationally intense and requires software to implement. This intensity stems from the need to create and process the input and output data associated with the hundreds or thousands of scenarios considered for a typical reliability reporting period. Due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

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 conditions that exist 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 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 chronologic order the set of analysis periods that comprise the reliability reporting period. This section overviews 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 following each weather event that the pavement remains wet or covered by snow or ice, as the presence of these conditions has been found to have an influence on running speed and intersection saturation flow rate.

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 non-crash), severity levels, and locations on the facility. Location is defined by the specific intersection or segment on which the incident occurs and whether the incident occurs on the

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

shoulder, in one lane, or in multiple lanes. The procedure incorporates weather and traffic demand variation information from the previous procedures when 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. Speeds are also 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 chronologic order.

First, the dataset associated with a given analysis period is evaluated 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, based on 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:

- 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 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 travel time index 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 will often reallocate some traffic lanes or alter the signal operation to increase the capacity of specific traffic movements. These characteristics make each work zone and special event unique, and their effect on facility performance equally 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 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 underway. A start date and duration is associated with each dataset.

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

When using the reliability methodology, the analyst must provide an estimate of traffic demand volumes during the work zone or special event. These estimates should reflect the effect of diversion, and can be based on past field measurements, judgment, or area-wide 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. This 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), then 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 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 also 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 comprise the reliability reporting period. Thus, it is important to replicate these random elements in any reliability evaluation. Monte Carlo methods are used for this purpose in the urban street reliability methodology.

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. In fact, 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, then 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 evaluating alternatives, the analyst will likely use one set of seed numbers as a variance reduction technique. In this application, the same seed

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

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 using 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 $1-\alpha$;

$t_{(1-\alpha/2), N-1}$ = 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 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.

Number of Replications	Student's t-Statistic for Two Values of α	
	$\alpha = 0.05$	$\alpha = 0.10$
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

Exhibit 36-21
Student's t-Statistic

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. These ratios were derived from a national freeway dataset developed by SHRP 2 Project L03 (11). 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)

Month	Day of Week						
	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 in Cambridge Systematics et al. (17).

Note: Ratios represent demand relative to a Monday in January.

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

Month	Day of Week						
	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 in Cambridge Systematics et al. (17).

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.

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

Source: Kittelson & Associates et al. (7).

Month	Incident Type				
	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: Kittelson & Associates et al. (7).

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 as these are based on a single site (see Exhibit 10-15 in Chapter 10).

Weather Type	Capacity Adjustment Factors					Speed Adjustment Factors				
	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.

Exhibit 36-24

Default Freeway Incident Severity Distributions

Exhibit 36-25

Default Freeway Incident Durations (min)

Exhibit 36-26

Default CAFs and SAFs by Weather Condition

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 several research projects and others are based on an aggregation of data from several 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 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 complete urban street incident records.

Traffic Demand Variability

Default hour-of-day, day-of-week, and month-of-year traffic demand adjustment factors are listed in Exhibit 36-27 through Exhibit 36-29, respectively. These 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. (73).

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. (73).

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 the National Climatic Data Center (7, 8). Exhibit 36-30 provides other 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% when it is snowing (14). These motorists likely altered the start time of their commute, or just 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 depending on 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 represents the ratio of hourly crash frequency during the weather event divided by the hourly crash rate during clear, dry hours. It is computed using one or more years of historic 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. Using a similar technique, the hourly crash frequency is computed for dry

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

Exhibit 36-30
Urban Street Weather-Related Default Values

Exhibit 36-31
Urban Street Incident Default
Values

pavement hours $f_{C_{dry}}$. The crash adjustment factor for the weather condition is computed as the ratio of the two frequencies (i.e., $CAF_{wea} = f_{C_{wea}} / f_{C_{dry}}$).

The crash adjustment factor includes consideration of the effect of the weather event on traffic volume (i.e., volume may be reduced due to 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%, then the crash frequency adjustment factor for rainfall is 2.70 ($= 3.0 \times 0.9$).

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: Kittelson & Associates, et al. (7).

Incident duration is computed as the sum of the incident detection time, response time, and clearance time. The incident detection time represents 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 represents the time period starting from the receipt of incident notification by officials to the time the first response vehicle arrives to the scene of the incident. It is likely that this time will 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 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. The reason segments and intersections are differentiated is 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.

Street Location	Event Type	Lane Location	Severity ^a	Clearance Time by Weather Condition (min)					
				Dry	Rain-fall	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: Kittelson & Associates, et al. (7).

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 36-32
 Default Urban Street Incident Clearance Times

Street Location	Event Type	Pro-portion	Lane Location	Pro-portion	Severity ^a	Pro-portion	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
	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: Kittelson & Associates, et al. (7).

Note: (a) FI = fatal or injury crash, PDO = property-damage-only crash, Other = not breakdown (e.g., debris).

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

Exhibit 36-34

Default Urban Street Incident Distribution Without Shoulder Presence

Street Location	Event Type	Pro-portion	Lane Location	Pro-portion	Severity ^a	Pro-portion	Joint Proportion
Segment	Crash	0.358	1 lane	0.837	FI	0.304	0.091
			2+ lanes	0.163	PDO	0.696	0.209
					FI	0.478	0.028
	Non-crash	0.642	1 lane	0.881	PDO	0.522	0.030
			2+ lanes	0.119	Breakdown	0.836	0.473
					Other	0.164	0.093
Signalized Intersection	Crash	0.310	1 lane	0.856	FI	0.378	0.100
			2+ lanes	0.144	PDO	0.622	0.165
					FI	0.412	0.018
	Non-crash	0.690	1 lane	0.859	PDO	0.588	0.026
			2+ lanes	0.141	Breakdown	0.849	0.503
					Other	0.151	0.089
						Total:	1.000

Source: Kittelson & Associates, et al. (7).

Note: (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 the ones listed in Exhibit 36-35:

Exhibit 36-35

Use Cases of Travel Time Reliability

Application	Use Cases for Travel Time Reliability
Long Range Transportation Plan	<ul style="list-style-type: none"> Identifying <u>existing</u> facilities not meeting reliability standards.
Transportation Improvement Program	<ul style="list-style-type: none"> Identifying <u>future</u> facilities not meeting reliability standards.
Corridor or Area Plans	<ul style="list-style-type: none"> Generating alternatives to address reliability problems.
Major Investment Studies	<ul style="list-style-type: none"> Evaluating reliability benefits of improvement alternatives.
Congestion Management	<ul style="list-style-type: none"> Prioritizing operational improvements and traditional capacity improvements.
Operations Planning	<ul style="list-style-type: none"> Evaluating the probability of achieving acceptable reliability and/or LOS.
Long-range Planning: Demand Forecasting	<ul style="list-style-type: none"> 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 used to generate and evaluate 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 to better identify improvement alternatives, evaluate their benefits, and more accurately prioritize them in relation to conventional capacity improvements.

Reliability also adds another dimension of information on facility performance that can aid travel demand models to better predict 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 #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. This use case 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 #2: Forecasting Future Problems

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

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

The forecasting questions that Case 2 addresses include:

3. 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.
4. 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. Predicting the effect of capacity improvements, demand changes, and Active Traffic Demand Management (ATDM) improvements on crash frequencies.
5. Dealing with congestion overflows (e.g., over the entry link, over the last analysis period) when computing performance measures and comparing to existing conditions.
6. Calibrating this chapter’s forecasted reliability for future conditions to field-measured reliability under existing conditions (for data-rich agencies).

Use Case #3: Generating Alternatives

This use case identifies alternative operational and capacity improvements for addressing reliability problems, including selecting operational and capacity

improvements that are likely to best address the identified primary causes of reliability problems on the facility.

This case requires that the analyst:

1. Determine that a reliability problem exists (see Use Case #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 possible 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 #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 #3 was primarily about diagnosis, Use Case #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 #3 diagnosis chart with locally specific treatment options.

Use Case #5: Prioritizing Improvements

This use case applies reliability performance measures in combination with other performance measures to prioritize investments in operational and capacity improvements. Estimating the relative values of mean travel time improvements and travel time reliability improvements are 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 to 95th percentile travel time or some other measure of reliability?

Use Case #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. As such, it is a critical input to the diagnostic process of Use Case #3. No diagnosis is needed when it is determined that no reliability problem exists. However, if Use Case #6 determines that a problem exists, then Use Case #3 is used to diagnose the causes and identify promising treatment options.

Use Case #6 shares much with Case #5, but it introduces a new concept, acceptability or failure. The numerical results produced in Use Case #5 are compared to 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 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 #5 deals with numerical outputs that are compared relative to each other (relativistic evaluation). In contrast, Use Case #6 compares the numerical outputs to an absolute standard (failure analysis).

Use Case #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 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 non-toll) algorithm.

Use Case #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

There will be cases where 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 when 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 it is possible to apply this chapter's conceptual framework for evaluating travel time reliability to alternative analysis tools. The same conceptual approach of generating scenarios, assigning scenario probabilities, evaluating scenario performance, and summarizing the results applies when using alternative analysis tools, such as microsimulation, to estimating 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 using 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. Specifically:

- Scenarios may be defined differently 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 would no longer be applied. They would be replaced with the analysis tool's built-in randomization process.
- The urban street randomization factor for 15-min demands would no longer be applicable. It would 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 would have to be converted by the analyst to the microsimulation model equivalents: desired speed distribution and desired headway distribution. Acceleration and deceleration rates would also be affected for some weather events.
- This chapter's recommended freeway speed-flow curves for weather events and incidents would be replaced with adjustments to the model's car-following parameters, such as desired FFS, 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 running the scenarios. Application guidance and typical factors are provided in the 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), then many of this chapter's adaptations of the conceptual analysis framework to the HCM may still be appropriate or may need to be further aggregated. 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

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

Exhibit 36-36
List of Example Problems

The example problems in this section demonstrate the application of the freeway facility (Example Problems 1–5) and urban street (Example Problems 6–7) reliability methods. They illustrate the general process of applying the methods that is described in this chapter, but also 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.

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.

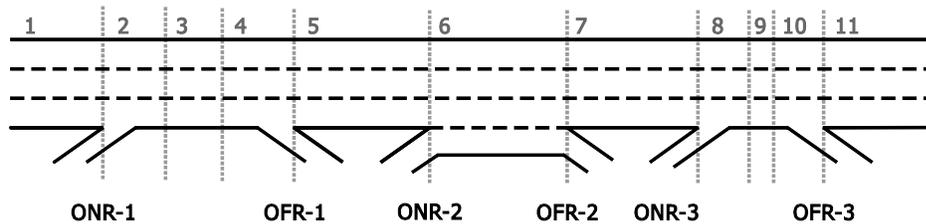


Exhibit 36-37
Example Problem 1: Freeway Facility Schematic

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

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

Note: 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. Calculating a variety of reliability statistics for a freeway facility using the minimum required data,
2. Identifying key reliability problems on the facility, and
3. Testing 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 10–13) 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 p.m. to 7 p.m., which covers the p.m. peak hour and shoulder periods. This period is selected for reliability analysis because it is when recurring congestion is typically present in the study direction of this facility. 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-minute analysis period in the base dataset. Care should be taken to make sure 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 vehicle-miles travelled (VMT). Furthermore, an earlier study conducted by the state that the facility is located in found that an average of 7 incidents occur for every 1 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 being 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.

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

Exhibit 36-40

Example Problem 1: Demand Ratios Relative to AADT

An inspection of these demand patterns finds 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 $5 \text{ days} \times 12 \text{ months} = 60$ demand patterns into a smaller set of $2 \times 4 = 8$ 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 (ignoring small differences in the number of days per month). 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 twelve 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 FFS 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, while 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	Weather Event Probability (%)			
	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, it is desirable to have detailed incident logs that can be used to develop monthly or seasonal probabilities of various incident severities. However, in this case, incident logs of sufficient detail are not available.

Therefore, the alternative method of using local crash rates and ratios of incidents to crashes, in combination with default values, is used to estimate incident probabilities and severities. 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.

Continuing 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).

Then, the expected number of incidents is $(150 \times 10^{-8}) \times 7 \times 71,501 \times (1.07 / 1.00) = 0.803$ incidents 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 are used. For example, from Exhibit 36-24, 75% of all incidents nationally are shoulder-closure incidents. Because full-facility closures (i.e., all 3 lanes in the case of this facility) are not modeled by the reliability method, the probability of a 3+ lane closure is combined with that of a 2-lane closure, resulting in a 5% probability of a 2-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).

Therefore, with 0.803 incidents 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:

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

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 of 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:

- 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) = $0.10 \times (1 - 0.8568) \times (1 - 0.9808) = 0.03\%$

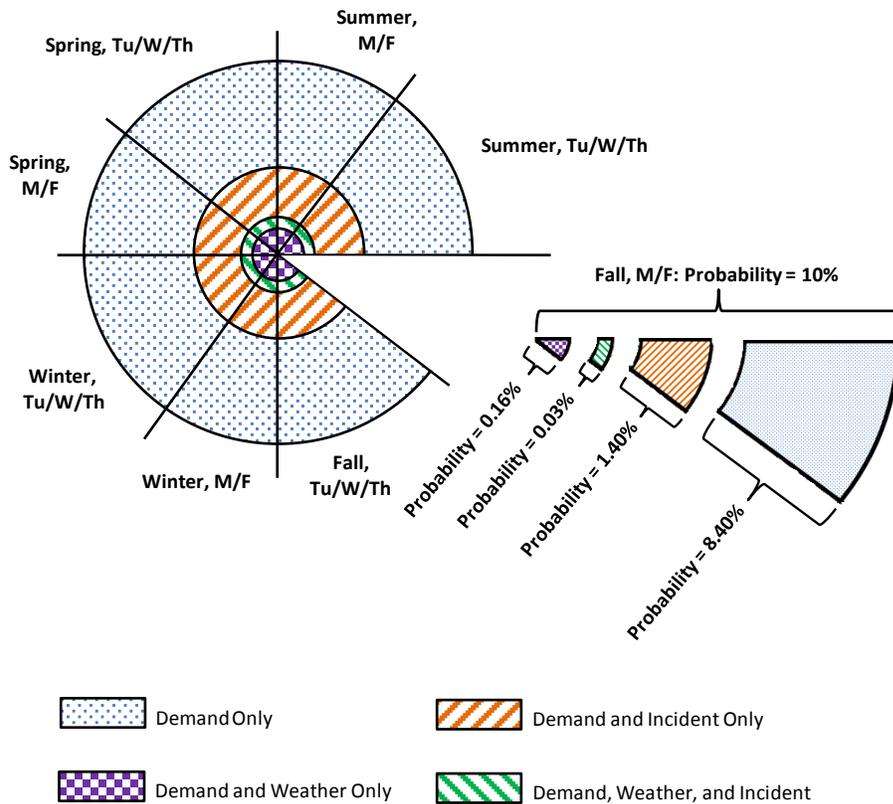


Exhibit 36-44
Example Problem 1:
Probabilities of Combinations
of Demand, Weather, and
Incidents

As a check, these probabilities add up to 10%, after accounting for rounding errors. 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.

Scenario Description	Number of Scenarios		Percentage of Scenarios	
	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%

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

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 snow storm) that fall below the inclusion threshold; however, these scenarios may also be so rare that they do not occur every year (or only every few years). If low-probability scenarios are discarded, the probabilities of all discarded scenarios are proportionally reassigned to the remaining scenarios.

This main reason for choosing this approach is to significantly reduce the number of scenarios evaluated using the Chapter 10 freeway facilities methodology and the corresponding analysis time. If the analysis time is not an issue, then 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 can be seen 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:
 - Type of the weather event (rain, snow, low visibility, etc.)
 - Duration of the weather event (average duration only)
 - Start time of the weather event (either at the beginning or halfway in the study period)
- Whether an incident is present and if so:
 - Severity of the incident (shoulder closure, single or multiple lane closures)
 - Duration of the incident event (25th, 50th, and 75th percentile of default distribution)
 - Start time of the incident event (either at the beginning or halfway in the study period)
 - Location on the incident on facility (3 locations, on first, last, and midpoint segments)
- Whether a combination of weather and incident events are 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 then be used to generate a variety of reliability performance measures.

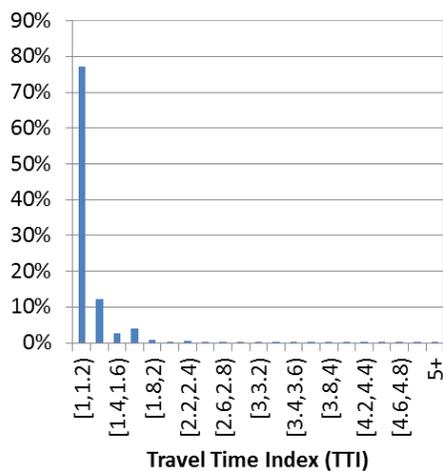
Results and Discussion

Exhibit 36-46 provides key reliability performance measure results for this example problem, based on a scenario inclusion threshold of 0.01%, involving a total of 602 scenarios. The exhibit provides the results for just 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.

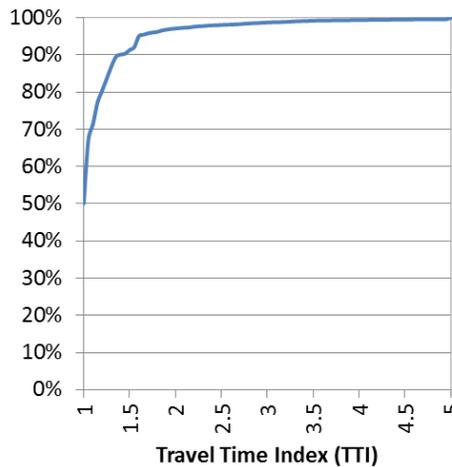
Reliability Performance Measure	Value for Base Scenario	Value from all Scenarios	Percent Difference
Mean facility TTI (corresponding speed, mi/h)	1.04 (57.7)	1.21 (49.7)	+16%
PTI (corresponding speed, mi/h)	Unavailable	1.65 (36.4)	N/A
Maximum observed facility TTI (speed, mi/h)	1.09 (55.0)	37.1 (1.6)	+3300%
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 non-recurring congestion	Unavailable	12.6	N/A

Notes: N/A = not applicable, VHD = vehicle-hours of delay.

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



(a) Probability Distribution Function



(b) Cumulative Distribution Function

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

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 impact of incidents and weather are typically not taken into account. For an operating agency, knowing

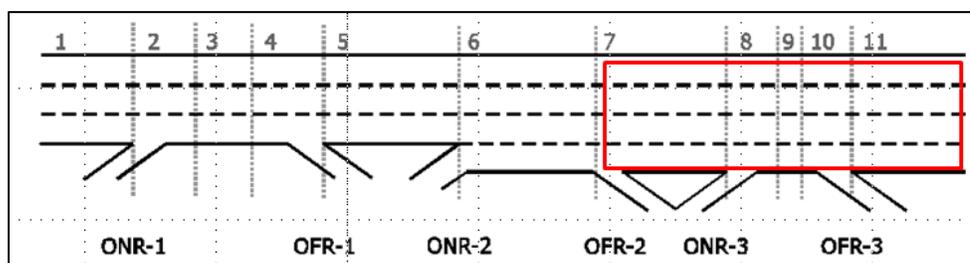
that 85% of the facility's VMT during the p.m. peak period operates at a speed of 45 mi/h or higher is an important benchmark. It is also clear that much of the facility's delay is due to demand variability and the effect of weather and incidents.

It is worthwhile considering whether using a scenario inclusion threshold of 0.01% substantially affected the reliability performance measure results. 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 materially change any conclusions or comparisons.

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 as 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 2-lane closure in this portion of the facility is 3.1%, while the probability of a 3-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 3 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.

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)	+3500%
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 non-recurring congestion	Unavailable	6.1	N/A

Notes: N/A = not applicable, VHD = vehicle-hours of delay.

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

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 significant enough to recommend the major improvement.

On the other hand, the mean TTIs 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 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 non-construction 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 incidents to be cleared faster 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, based on 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 the results one would obtain 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, while using 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)	+2850%
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 non-recurring congestion	Unavailable	8.1	N/A

Notes: N/A = not applicable, 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 to Example Problem 1. The largest improvement is in the misery index, which improves from 3.00 (20 mi/h) to 2.47 (24.4 mi/h), a 20% improvement. It appears that the proposed treatment, while not necessarily impacting average operations, would have a positive effect on reducing the severity of extreme cases combining both 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 minutes. 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: as seen by comparing the results of base scenario from Example Problems 1 and 3, the base scenario results are the same. Only by incorporating the effects of incidents on travel time, as this chapter's reliability method does, can the effectiveness of incident management treatments on a facility be evaluated.

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. These incident probabilities are modified as shown in Exhibit 36-52, based on 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 the results one would obtain in a real-world situation.

Demand Pattern	Incident Probability			
	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.

Exhibit 36-52

Example Problem 4: Incident Probabilities by Demand Pattern

Results and Discussion

The key congestion and reliability statistics for this example problem are summarized in Exhibit 36-61. The total number of possible scenarios remains 1,928, while using 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%.

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)	+3300%
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 non-recurring congestion	Unavailable	7.4	N/A

Notes: N/A = not applicable, VHD = vehicle-hours of delay.

Exhibit 36-53

Example Problem 4: Summary Reliability Performance Measure Results

Similar to Example Problem 3, it appears that average facility operations improve slightly compared to 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 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, as 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. By reducing peak-period demand, a capacity buffer is provided that can possibly 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 36-52 (flattening the peak), based on 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 the results one would obtain 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.

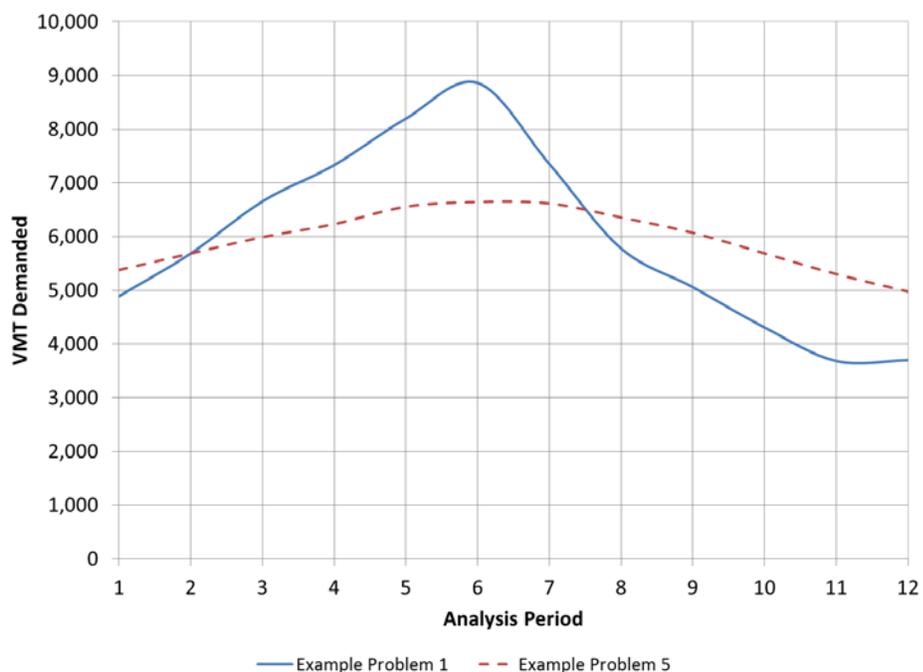


Exhibit 36-55
Example Problem 5:
Comparison of VMT Demand
by 15-min Analysis Periods

Results and Discussion

Exhibit 36-58 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 using a 0.01% scenario inclusion threshold).

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)	+2900%
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 non-recurring congestion	Unavailable	9.6	N/A

Notes: N/A = not applicable, VHD = vehicle-hours of delay.

On average, the facility shows significant operational improvements compared to 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 also 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 36-56
Example Problem 5: Summary
Reliability Performance
Measure Results

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	51.7	53.6
PTI	1.65	1.16	1.61	1.61	1.29
Reliability rating (%)	85.0%	97.4%	87.3%	87.3%	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 non-recurring 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 incident or weather events. Since this is a bottleneck treatment that addresses a recurring congestion problem, the share of delay due to non-recurring events increased.
- Demand management had the second most beneficial effect on the absorption of the recurring congestion problem.
- Both the incident management and safety treatments produced similar positive effects compared to 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 non-recurring congestion had the smallest share of VHD with this treatment.
- Safety treatments and incident management strategies affect the tail of 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 using a traditional HCM analysis that only considers recurring congestion effects during a single study period.
- A host of other treatments related to Active Traffic Demand Management can be tested using 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.
- An important limitation of the analysis presented in these examples is the assumption that travel demand is insensitive to severe weather or incident conditions. It is likely under such scenarios that travelers may

alter their route, departure time, or mode, or 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 using the minimum required data for the analysis,
- Identifying the key reliability problems on the facility, and
- Diagnosing 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 located in Lincoln, Nebraska. The street is a two-way, four-lane, divided roadway with shoulders. There are seven signalized intersections that 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.

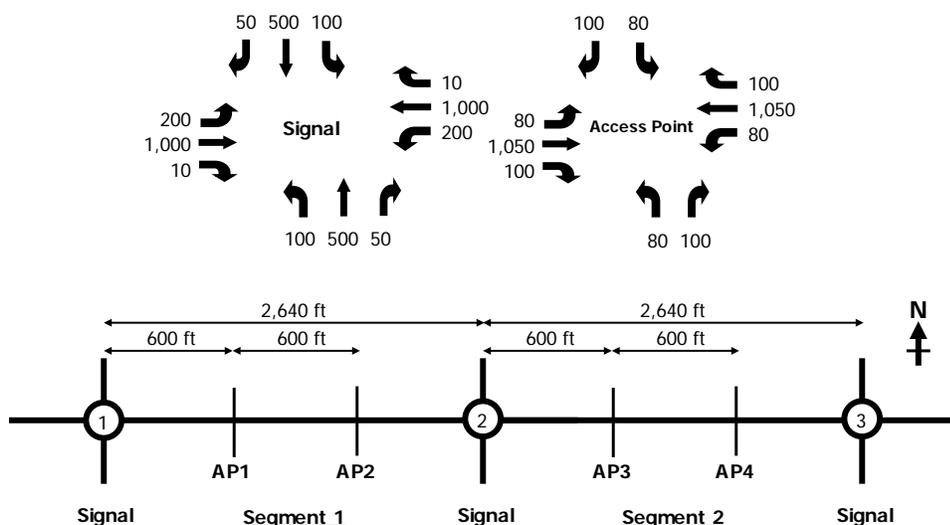


Exhibit 36-58
Example Problem 6: Urban Street Facility

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

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 #1. The other signalized intersections have the same signal timing.

Approach Movement	Eastbound			Westbound			Northbound			Southbound		
	L	T	R	L	T	R	L	T	R	L	T	R
NEMA Movement #	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 #1 through #7, respectively.

Analysis Replications

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 are 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.

Exhibit 36-60

Example Problem 6:
Intersection #1 Signal Timing
Data

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 accurately determine the frequency (or probability) of the subject variable's value.

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

Because events (e.g., a storm, a crash) are generated randomly in the urban street method, the possibility exists that 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 are 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.

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 employed in the analysis. As a result, evaluating the same dataset and seed number in different software or on a different platform may result in different results than shown here. Each result, though different, 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 if the facility is experiencing significant reliability problems. They also want 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, non-incident conditions. A study period consisting of the weekday morning peak period (7 a.m. to 10 a.m.) and a study area consisting of the 3-mi length of facility between intersections #1 and #7 encompasses all of the recurring congestion.

The reliability reporting period is desired to 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 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. It was determined that reliability problems associated with work zones and special events were not 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

As 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 the NCDC (7, 8) 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

Exhibit 36-61

Example Problem 6: Sample
Weather Data for Lincoln,
Nebraska

- 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 two months of the year.

Weather Data	January	April
Normal precipitation (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: *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 if precipitation will occur in a given day. If yes, 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 non-holiday weeks in January and two non-holiday 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 perfectly correlated with the precipitation rate such that storms producing a large total precipitation are associated with a high precipitation rate. This relationship is replicated by estimating both values 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.

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.

Exhibit 36-62

Example Problem 6: Sample
Generated Weather Events

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 a.m. 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. 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 May 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 snowing 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
- 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 non-holiday days of the year, this table illustrates the computations for selected days when dry weather or snow are 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.

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

Exhibit 36-63

Example Problem 6: Sample Demand Profile Calculations

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 non-crash), 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 incidents and non-crash-related incidents.

For an urban street reliability evaluation, incidents are categorized as being:

- Segment-related, or
- 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 non-crash incidents is estimated from the crash frequency data in a subsequent step. Non-crash incident frequency is not an input quantity due to the difficulty agencies have in acquiring non-crash incident data.

Exhibit 36-64

Example Problem 6: Locally Available Crash Frequency Data

Location	Crash Frequency (cr/yr)
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/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 adjustment factor corresponding to each weather condition. For this example problem, the number of hours in a year with particular weather condition is determined from the default weather data for Lincoln, Nebraska.

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

$$F_{C_{str(i),dry}} = \frac{F_{C_{str(i)}} 8,760 Ny}{Nh_{dry} + CAF_{rf} Nh_{rf} + CAF_{wp} Nh_{wp} + CAF_{sf} Nh_{sf} + CAF_{sp} Nh_{sp}}$$

$$F_{C_{str(i),wea}} = F_{C_{str(i),dry}} CAF_{wea}$$

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.

This equation and the equations that follow are explained in Section 5, Urban Street Scenario Generation, in Chapter 37.

Variable	Definition	Segments		Intersections		
		1-2	2-3	1	2	3
$F_{Cstr(i)}$	Observed average crash frequency	15	16	65	66	67
N_y	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/ice on pavement	45.86	45.86	45.86	45.86	45.86
	Crash adjustment factors for...					
CAF_{rf}	Rainfall	2.0	2.0	2.0	2.0	2.0
CAF_{wp}	Wet pavement	3.0	3.0	3.0	3.0	3.0
CAF_{sf}	Snowfall	1.5	1.5	1.5	1.5	1.5
CAF_{sp}	Snow/ice on pavement	2.75	2.75	2.75	2.75	2.75
	Calculated crash frequencies for...					
$F_{Cstr(i),dry}$	Dry weather	14.50	15.47	30.94	31.91	32.88
$F_{Cstr(i),rf}$	Rainfall	29.01	30.94	61.89	63.82	65.75
$F_{Cstr(i),wp}$	Wet pavement	43.51	46.41	92.83	95.73	98.63
$F_{Cstr(i),sf}$	Snowfall	21.76	23.21	46.41	47.86	49.32
$F_{Cstr(i),sp}$	Snow/ice on pavement	39.89	42.54	85.09	87.75	90.41

Note: Hours of dry, rainfall, wet pavement, snowfall, and snow/ice on pavement sums to 17,520 h (2 yr).

Exhibit 36-65

Example Problem 6:
Computation of Crash
Frequency by Weather Type

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, it is determined if an incident occurs. If an incident occurs, then its duration is also determined. Finally, for each incident identified in this manner, it is determined whether some portion (or all) of the incident occurs during a portion of the study period.

Weather-Adjusted Incident Frequencies. First, for a given hour in a given day, the weather event data are checked to see which weather condition (dry, rainfall, snowfall, wet pavement and not raining, or snow/ice on pavement and not snowing) was generated for that hour. The expected incident frequencies for street locations (i.e., segments and intersections) $F_{i_{str(i),wea}(h,d)}$ are determined from: (1) the corresponding crash frequency for the given weather condition $F_{C_{str(i),wea}}$ (from a previous step) and (2) 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 adjustment factor CAF_{str} specified by the analyst for special events and work zones. The following equation is used:

$$F_{i_{str(i),wea}(h,d)} = CAF_{str} \frac{F_{C_{str(i),wea}}}{pc_{str,wea}}$$

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/yr (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 adjustment factor is 1.0. Then:

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

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 cr/yr. The ratio of crashes to incidents for segments in snowy weather is 0.358. Therefore,

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

Conversion to Hourly Frequencies. Next, the incident frequency $F_{i_{str(i),wea(h,d)}}$ is converted to an hourly frequency $f_{i_{str(i),wea(h,d),h,d}}$ 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” represents the number of hours in a year and “24” represents the number of hours in a day.

$$f_{i_{str(i),wea(h,d),h,d}} = \frac{F_{i_{str(i),wea(h,d)}}}{8,760} (24 f_{hod,h,d}) f_{dow,d} f_{moy,d}$$

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

$$f_{i_{seg1-2,dry,0700,Jan10}} = \frac{(40.5)}{(8,760)} (24 \times 0.047) (1.00) (0.987) = 0.00515 \text{ incidents/h}$$

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

$$f_{i_{seg1-2,sf,0800,Jan12}} = \frac{(60.8)}{(8,760)} (24 \times 0.071) (0.980) (0.831) = 0.00963 \text{ incidents/h}$$

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

$$p_{0_{str(i),wea(h,d),con,lan,sev,h,d}} = \exp(-f_{i_{str(i),wea(h,d),h,d}} \times p_{i_{str(i),wea(h,d),con,lan,sev}})$$

where

$p_{0_{str(i),wea(h,d),con,lan,sev,h,d}}$ = 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;

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

$p_{i_{str,wea(h,d),con,lan,sev}}$ = 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.

Incident Type			Incident Proportion	Hourly Incident Frequency	exp (- $f/l \times p$)	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
Non-crash	1 lane	Breakdown	0.456	0.00515	0.99766	0.99900	Yes
Non-crash	1 lane	Other	0.089	0.00515	0.99954	0.59842	No
Non-crash	2 lane	Breakdown	0.059	0.00515	0.99970	0.69323	No
Non-crash	2 lane	Other	0.017	0.00515	0.99991	0.08131	No
Non-crash	Shoulder	Breakdown	0.014	0.00515	0.99993	0.13012	No
Non-crash	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. They are not necessarily the same results that would be achieved in a full run of the procedure.

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 (- $f/l \times p$)	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
Non-crash	1 lane	Breakdown	0.456	0.00963	0.99562	0.40513	No
Non-crash	1 lane	Other	0.089	0.00963	0.99914	0.98428	No
Non-crash	2 lane	Breakdown	0.059	0.00963	0.99943	0.61918	No
Non-crash	2 lane	Other	0.017	0.00963	0.99983	0.13712	No
Non-crash	Shoulder	Breakdown	0.014	0.00963	0.99987	0.30502	No
Non-crash	Shoulder	Other	0.007	0.00963	0.99993	0.33279	No

Note: Incident proportions total 100%. PDO = property damage only.

Random numbers have been selected to illustrate this particular step of the computations. They are not necessarily the same results that would 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

If more than one incident occurs at the same time and location, then 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, then 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, then 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 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. This rounding is performed to ensure the most representative match between event duration and analysis period start/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 non-crash, 1-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
<i>Location</i>	Segment 1-2
<i>Incident type</i>	Non-Crash
<i>Number of lanes involved</i>	1-lane
<i>Incident severity</i>	Breakdown
<i>Weather</i>	Dry
<i>Incident detection time (min)</i>	2.0
<i>Incident response time, dry weather (min)</i>	15.0
<i>Incident clearance time (min)</i>	10.8
<i>Average incident duration (min)</i>	27.8
<i>Standard deviation of incident duration (min)</i>	22.2
<i>Average incident duration (h)</i>	0.463
<i>Standard deviation of incident duration (h)</i>	0.371
<i>Random number</i>	0.57455
<i>Gamma function alpha parameter (mean²/variance)</i>	1.5625
<i>Gamma function beta parameter (variance/mean)</i>	0.2965
<i>Duration (h)</i>	0.433
<i>Rounded duration (nearest 15 min) (h)</i>	0.50
<i>Incident start time</i>	9:00
<i>Incident end time</i>	9:30

Determine Incident Location

If an incident occurs at a segment or intersection during a given hour and day, then 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 have 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, then 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/hours $\times 3$ hours/day $\times 5$ days/week $\times 52$ weeks/year $\times 1$ 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/ice on the pavement then 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 the HCM 2010. However, this methodology includes an additional procedure that so the methodology 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, is computed for each scenario.

Step 8: Conduct Quality Control and Error Checking

It is difficult to quality control thousands of scenarios, so 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 it 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) such 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. These results are listed in Exhibit 36-69. Although both travel directions have the same volume and capacity, several of the values in this exhibit vary slightly by travel direction due to the use of Monte Carlo methods.

Exhibit 36-69

Example Problem 6: Reliability Performance Measure Results

Measure	Eastbound	Westbound
Vehicle-miles traveled ^a	2260	2257
Number of scenarios ^a	3120	3120
Base free-flow travel time, s ^b	262.9	262.9
Mean TTI ^b	1.69	1.64
80 th percentile TTI	1.57	1.56
95 th percentile TTI (PTI)	2.98	2.61
Reliability rating	93.2	94.1
Total delay (veh-h) ^b	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).

The vehicle-miles traveled (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 both 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 a LOS D or better for that scenario. The reliability ratings shown in the exhibit indicate that more than 90% of the vehicle-miles of travel 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 listed in Exhibit 36-69 that considers the performance of all traffic movements (i.e., the other measures consider just the major-street through

movement). Hence, it is useful for quantifying the overall change in operation associated with a strategy. When considered on a scenario-by-scenario basis, this statistic can be used to identify those 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.

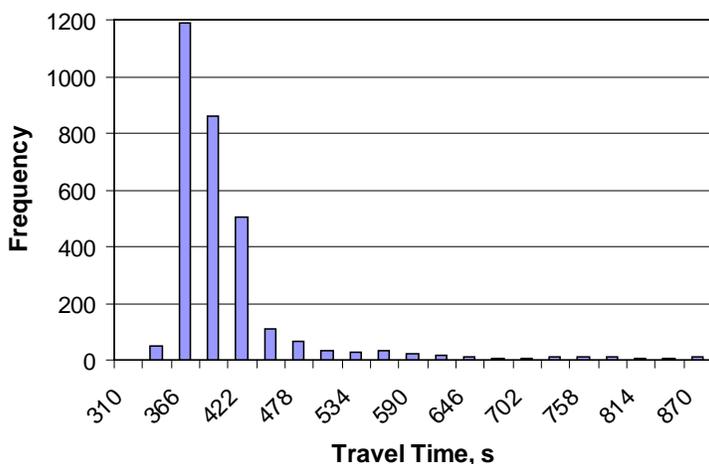


Exhibit 36-70
Example Problem 6:
Eastbound Travel Time
Distribution

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 using Equation 36-7. The confidence interval for the average travel time is 432.2 to 441.1 s, which equates to $\pm 1.36\%$ of the overall average travel time. Similarly, the confidence interval for the 95th percentile travel time is $\pm 3.16\%$ 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
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% confidence interval	432.2–444.1 (±1.36%)	744.4–792.8 (±3.16%)

The contribution of demand, incidents, and weather to total vehicle-hours of delay (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		Total
	Fair Weather	Foul Weather	Fair Weather	Foul Weather	
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		Total
	Fair Weather	Foul Weather	Fair Weather	Foul Weather	
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 on the urban street example is high demand, accounting for 53.6% of annual delay during fair weather with no incidents. Incidents or 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 when evaluating improvement strategies. The strategies considered in this example involve changes to the urban street's geometric design or its signal operation. These changes are shown to have an impact on 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 to the base datasets. However, it should be noted that some strategies may require changes to 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, non-incident conditions. A study period consisting of the weekday morning peak period (7 a.m. to 10 a.m.) and a study area consisting of the 3-mi length of facility between intersections #1 and #7 encompasses all of the recurring congestion.

The reliability reporting period is desired to 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 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 *Highway Safety Manual (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 was 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 *Highway Safety Manual (4)* indicates that intersection crash frequency increases by 9% for this change. Therefore, the crash frequency input data for each intersection was increased to reflect this change.

Code the Alternative Datasets

As 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 are created associated with each strategy. 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 revealed 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 listed 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.

Case	Travel Time (s)		Total Delay (veh-h)	Reliability Rating
	Average	95th Percentile		
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

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

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)		Total Delay (veh-h)	Reliability Rating
	Average	95th Percentile		
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 listed in Exhibit 36-76.

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

Case	Travel Time (s)		Total Delay (veh-h)	Reliability Rating
	Average	95th Percentile		
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 include considering 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.

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

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CHAPTER 37

TRAVEL TIME RELIABILITY: SUPPLEMENTAL

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1. RELIABILITY VALUES FOR SELECTED U.S. FACILITIES

DATA SOURCES

One year of non-holiday weekday travel time reliability data were obtained from the following sources:

- Year 2010, 2-min traffic speed data in the I-95 corridor (1), and
- Year 2010, 5-min traffic speed data in California (2).

The first dataset includes freeway and urban street reliability data for states and metropolitan areas in the I-95 corridor (i.e., U.S. East Coast). The average speed of traffic was measured every 2 min for each Traffic Message Channel (TMC) road segment (3). Road segments vary, but generally terminate at a decision point for the driver (e.g., intersection, start of left turn pocket, ramp merge or diverge). Traffic speeds are obtained by monitoring the positions of Global Positioning System (GPS) units in participating vehicles. A “free-flow reference speed” is also established for each TMC segment, but the method used to establish the reference speed is not disclosed.

The California data include freeway reliability data for the state’s major metropolitan areas, plus reliability data for one urban street in Chula Vista. The data come from two sources: toll tag readers and loop detectors. California’s system provides a function for stringing together a series of loop detector station speeds into an estimate of the overall average speed for the facility. The loop detector data used to compute an average speed for each segment of the facility is offset by the amount of time it takes the average vehicle to traverse the upstream segment. Thus for a selected direction of travel, the average speed of vehicles in segment one is used to compute the average travel time t for the selected analysis period (e.g., 5 min) for that segment starting at time $T = 0$. The mean speed is computed for the next downstream segment for the 5-min analysis period starting at $T = 0 + t$. The resulting mean travel times are then added together to get the average travel time of vehicles for the 5-min analysis period starting their trip at $0 < T < 5$ min.

RELIABILITY STATISTICS FOR A CROSS-SECTION OF U.S. FACILITIES

Exhibit 37-1 through Exhibit 37-4 show the distribution of mean travel time index (mean TTI) and planning time index (PTI) observed in the dataset of U.S. freeways and urban streets described above, for all time periods combined, the 2-h a.m. peak period, the 2-h midday period, and the 2-h p.m. peak period, respectively. These exhibits are expanded versions of Exhibit 36-6, providing values in 5% percentile increments and including a combined set of values.

Exhibit 37-1

Rankings of U.S. Facilities by Mean TTI and PTI (A.M. Peak, Middy, and P.M. Peak Combined)

Percentile Rank	Freeways			Urban Streets		
	TTI	Mean TTI	PTI	TTI	Mean TTI	PTI
Minimum	1.01	1.02	1.07	1.03	1.06	1.23
Worst 95%	1.02	1.05	1.09	1.09	1.12	1.27
Worst 90%	1.02	1.06	1.13	1.13	1.15	1.29
Worst 85%	1.04	1.06	1.14	1.15	1.16	1.32
Worst 80%	1.05	1.08	1.17	1.17	1.20	1.33
Worst 75%	1.05	1.08	1.22	1.19	1.20	1.35
Worst 70%	1.05	1.09	1.25	1.19	1.22	1.36
Worst 65%	1.06	1.10	1.30	1.20	1.22	1.39
Worst 60%	1.07	1.12	1.34	1.20	1.23	1.41
Worst 55%	1.08	1.15	1.39	1.21	1.23	1.42
Worst 50%	1.10	1.16	1.47	1.23	1.26	1.44
Worst 45%	1.11	1.19	1.57	1.24	1.27	1.47
Worst 40%	1.13	1.23	1.73	1.25	1.28	1.49
Worst 35%	1.14	1.30	1.84	1.25	1.29	1.52
Worst 30%	1.17	1.33	1.97	1.26	1.30	1.54
Worst 25%	1.20	1.39	2.24	1.30	1.34	1.60
Worst 20%	1.26	1.43	2.71	1.33	1.36	1.63
Worst 15%	1.31	1.51	2.90	1.35	1.38	1.70
Worst 10%	1.59	1.78	3.34	1.39	1.47	1.84
Worst 5%	1.75	1.97	3.60	1.45	1.54	1.98
Maximum	2.55	2.73	4.73	1.60	1.66	2.55

Source: Derived from directional values in Exhibit 37-5 through Exhibit 37-10. Entries are the lowest value for a category.

Note: 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 37-2

Rankings of U.S. Facilities by Mean TTI and PTI (A.M. Peak)

Percentile Rank	Freeways			Urban Streets		
	TTI	Mean TTI	PTI	TTI	Mean TTI	PTI
Minimum	1.01	1.02	1.07	1.03	1.06	1.24
Worst 95%	1.01	1.03	1.08	1.08	1.12	1.24
Worst 90%	1.03	1.05	1.12	1.12	1.13	1.27
Worst 85%	1.04	1.06	1.14	1.13	1.15	1.29
Worst 80%	1.04	1.08	1.14	1.14	1.16	1.29
Worst 75%	1.05	1.08	1.17	1.15	1.16	1.31
Worst 70%	1.06	1.09	1.24	1.16	1.17	1.33
Worst 65%	1.07	1.10	1.36	1.18	1.20	1.35
Worst 60%	1.08	1.11	1.40	1.19	1.20	1.37
Worst 55%	1.08	1.16	1.47	1.19	1.21	1.39
Worst 50%	1.09	1.17	1.53	1.20	1.23	1.41
Worst 45%	1.11	1.19	1.58	1.20	1.24	1.42
Worst 40%	1.12	1.21	1.70	1.22	1.26	1.44
Worst 35%	1.13	1.21	1.78	1.24	1.27	1.50
Worst 30%	1.15	1.25	1.89	1.24	1.28	1.52
Worst 25%	1.20	1.42	2.13	1.25	1.29	1.54
Worst 20%	1.28	1.48	2.61	1.26	1.29	1.57
Worst 15%	1.54	1.83	3.17	1.26	1.29	1.66
Worst 10%	1.72	1.93	3.55	1.28	1.31	1.71
Worst 5%	1.95	2.08	3.92	1.35	1.36	1.84
Maximum	2.17	2.73	4.66	1.38	1.49	2.13

Source: Derived from directional values in Exhibit 37-5 through Exhibit 37-10. Entries are the lowest value for a category.

Note: 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.

Percentile Rank	Freeways			Urban Streets		
	TTI	Mean TTI	PTI	TTI	Mean TTI	PTI
Minimum	1.02	1.03	1.07	1.05	1.07	1.23
Worst 95%	1.02	1.04	1.08	1.08	1.10	1.27
Worst 90%	1.02	1.05	1.11	1.15	1.18	1.28
Worst 85%	1.02	1.06	1.14	1.16	1.18	1.30
Worst 80%	1.03	1.06	1.15	1.18	1.20	1.33
Worst 75%	1.04	1.08	1.17	1.19	1.21	1.34
Worst 70%	1.05	1.08	1.20	1.19	1.22	1.37
Worst 65%	1.05	1.09	1.21	1.20	1.22	1.39
Worst 60%	1.05	1.09	1.24	1.20	1.23	1.41
Worst 55%	1.06	1.11	1.26	1.21	1.23	1.42
Worst 50%	1.06	1.12	1.32	1.22	1.24	1.45
Worst 45%	1.07	1.13	1.34	1.24	1.27	1.47
Worst 40%	1.09	1.15	1.37	1.25	1.29	1.48
Worst 35%	1.09	1.15	1.43	1.25	1.30	1.51
Worst 30%	1.10	1.17	1.51	1.27	1.32	1.53
Worst 25%	1.12	1.26	1.65	1.30	1.34	1.57
Worst 20%	1.14	1.30	1.92	1.31	1.34	1.60
Worst 15%	1.16	1.32	2.41	1.32	1.35	1.63
Worst 10%	1.17	1.42	2.85	1.33	1.38	1.63
Worst 5%	1.21	1.46	3.16	1.35	1.42	1.86
Maximum	1.31	1.76	3.96	1.47	1.55	2.01

Source: Derived from directional values in Exhibit 37-5 through Exhibit 37-10. Entries are the lowest value for a category.

Note: 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 37-3

Rankings of U.S. Facilities by Mean TTI and PTI (Midday)

Percentile Rank	Freeways			Urban Streets		
	TTI	Mean TTI	PTI	TTI	Mean TTI	PTI
Minimum	1.01	1.05	1.10	1.13	1.14	1.32
Worst 95%	1.03	1.06	1.14	1.13	1.15	1.35
Worst 90%	1.04	1.06	1.22	1.18	1.21	1.35
Worst 85%	1.05	1.08	1.24	1.20	1.22	1.36
Worst 80%	1.05	1.09	1.28	1.20	1.22	1.37
Worst 75%	1.06	1.10	1.31	1.21	1.23	1.40
Worst 70%	1.07	1.14	1.32	1.22	1.23	1.41
Worst 65%	1.11	1.16	1.38	1.23	1.25	1.42
Worst 60%	1.14	1.23	1.59	1.24	1.26	1.44
Worst 55%	1.14	1.30	1.72	1.24	1.27	1.47
Worst 50%	1.17	1.31	1.85	1.25	1.28	1.49
Worst 45%	1.20	1.34	1.94	1.25	1.29	1.50
Worst 40%	1.21	1.36	2.06	1.31	1.33	1.52
Worst 35%	1.23	1.38	2.25	1.34	1.36	1.59
Worst 30%	1.26	1.41	2.46	1.35	1.38	1.64
Worst 25%	1.29	1.48	2.62	1.39	1.44	1.68
Worst 20%	1.35	1.57	2.77	1.41	1.49	1.78
Worst 15%	1.61	1.71	2.93	1.41	1.52	1.83
Worst 10%	1.70	1.86	3.26	1.49	1.56	1.88
Worst 5%	1.76	1.99	3.54	1.56	1.60	2.10
Maximum	2.55	2.73	4.73	1.60	1.66	2.55

Source: Derived from directional values in Exhibit 37-5 through Exhibit 37-10. Entries are the lowest value for a category.

Note: 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 37-4

Rankings of U.S. Facilities by Mean TTI and PTI (PM Peak)

Exhibit 37-5 through Exhibit 37-7 present the source freeway data for the a.m. peak, midday, and p.m. peak periods respectively. Exhibit 37-8 through Exhibit 37-10 present the source urban street data for the a.m. peak, midday, and p.m. peak periods, respectively.

Exhibit 37-5
Freeway Reliability Values:
Weekday A.M. Peak Period

Location	Freeway	Length (mi)	FFS (mi/h)	Direction	Avg. Travel		
					Time (min)	Mean TTI	PTI
Delaware	I-495	11.5	65	NB	11.0	1.03	1.08
Delaware	I-495	11.6	65	SB	11.1	1.03	1.07
Delaware	I-95	13.4	60	NB	14.6	1.10	1.37
Delaware	I-95	13.1	61	SB	13.5	1.05	1.13
Los Angeles	I-10	4.6	64	EB	4.5	1.06	1.12
Los Angeles	I-10	4.6	65	WB	4.5	1.08	1.14
Los Angeles	I-210	4.6	66	EB	4.9	1.17	1.57
Los Angeles	I-210	4.6	69	WB	4.6	1.16	1.57
Maryland	I-495 ES	26.5	63	SB	28.0	1.10	1.42
Maryland	I-495 ES	26.7	62	NB	31.1	1.20	1.71
Maryland	I-495 WS	15.4	60	NB	18.3	1.19	1.68
Maryland	I-495 WS	15.3	61	SB	26.9	1.78	2.71
Pennsylvania	I-76	3.7	51	EB	4.7	1.08	1.22
Pennsylvania	I-76	3.6	49	WB	6.5	1.49	3.06
Philadelphia	I-76	3.7	51	EB	4.7	1.08	1.22
Philadelphia	I-76	3.6	49	WB	6.5	1.79	3.06
Sacramento	US 50	6.0	69	EB	5.7	1.10	1.27
Sacramento	US 50	6.0	71	WB	6.2	1.21	1.78
Sacramento	I-80	12.4	68	EB	11.5	1.06	1.14
Sacramento	I-80	12.4	67	WB	12.0	1.09	1.17
San Diego	I-5	10.6	71	NB	11.1	1.23	1.81
San Diego	I-5	10.6	72	SB	9.1	1.02	1.07
San Diego	I-15	3.9	70	NB	4.7	1.41	2.10
San Diego	I-15	3.9	69	SB	7.3	1.58	3.38
San Francisco	I-880	4.6	71	NB	4.6	1.17	1.47
San Francisco	I-880	4.8	67	SB	8.2	1.92	3.57
San Francisco	I-680	4.2	66	NB	4.8	1.26	1.92
San Francisco	I-680	4.7	65	SB	5.2	1.21	1.49

Notes: Mean TTI = mean travel time index (mean travel time divided by free flow travel time).

PTI = planning time index (95th percentile travel time divided by free flow travel time).

NB = northbound, SB = southbound, EB = eastbound, WB = westbound, ES = east side, WS = west side.

Exhibit 37-6
Freeway Reliability Values:
Weekday Midday Periods

Location	Roadway	Length (mi)	FFS (mi/h)	Direction	Avg. Travel		
					Time (min)	Mean TTI	PTI
Delaware	I-495	11.5	65	NB	11.0	1.03	1.07
Delaware	I-495	11.6	65	SB	11.3	1.05	1.11
Delaware	I-95	13.4	60	NB	13.9	1.05	1.20
Delaware	I-95	13.1	61	SB	13.8	1.08	1.34
Los Angeles	I-10	4.6	64	EB	4.5	1.06	1.15
Los Angeles	I-10	4.6	65	WB	4.5	1.08	1.14
Los Angeles	I-210	4.6	66	EB	4.8	1.16	1.32
Los Angeles	I-210	4.6	69	WB	4.4	1.10	1.18
Maryland	I-495 ES	26.5	63	SB	27.2	1.07	1.31
Maryland	I-495 ES	26.7	62	NB	28.2	1.09	1.42
Maryland	I-495 WS	15.4	60	NB	20.5	1.34	2.69
Maryland	I-495 WS	15.3	61	SB	19.8	1.30	2.26
Pennsylvania	I-76	3.7	51	EB	5.0	1.13	1.39
Pennsylvania	I-76	3.6	49	WB	6.2	1.43	2.95
Philadelphia	I-76	3.7	51	EB	5.0	1.13	1.39
Philadelphia	I-76	3.6	49	WB	6.2	1.72	2.95
Sacramento	US-50	6.0	69	EB	5.8	1.11	1.20
Sacramento	US-50	6.0	71	WB	5.9	1.15	1.47
Sacramento	I-80	12.4	68	EB	11.8	1.09	1.25
Sacramento	I-80	12.4	67	WB	11.9	1.08	1.14
San Diego	I-5	10.6	71	NB	9.3	1.03	1.07
San Diego	I-5	10.6	72	SB	9.5	1.06	1.21
San Diego	I-15	3.9	70	NB	3.8	1.13	1.23
San Diego	I-15	3.9	69	SB	4.1	1.24	1.61
San Francisco	I-880	4.6	71	NB	4.5	1.17	1.53
San Francisco	I-880	4.8	67	SB	5.6	1.31	1.96
San Francisco	I-680	4.2	66	NB	4.4	1.15	1.34
San Francisco	I-680	4.7	65	SB	5.0	1.15	1.26

Notes: Mean TTI = mean travel time index (mean travel time divided by free flow travel time).

PTI = planning time index (95th percentile travel time divided by free flow travel time).

NB = northbound, SB = southbound, EB = eastbound, WB = westbound, ES = east side, WS = west side.

Location	Roadway	Length (mi)	FFS (mi/h)	Direction	Avg. Travel Time (min)	Mean TTI	PTI
Delaware	I-495	11.5	65	NB	11.4	1.06	1.23
Delaware	I-495	11.6	65	SB	12.0	1.10	1.39
Delaware	I-95	13.4	60	NB	14.6	1.10	1.29
Delaware	I-95	13.1	61	SB	16.8	1.30	1.83
Los Angeles	I-10	4.6	64	EB	5.1	1.20	1.31
Los Angeles	I-10	4.6	65	WB	4.9	1.16	1.28
Los Angeles	I-210	4.6	66	EB	4.5	1.08	1.35
Los Angeles	I-210	4.6	69	WB	4.2	1.06	1.15
Maryland	I-495 ES	26.5	63	SB	33.3	1.31	1.85
Maryland	I-495 ES	26.7	62	NB	33.7	1.31	1.98
Maryland	I-495 WS	15.4	60	NB	41.8	2.73	4.73
Maryland	I-495 WS	15.3	61	SB	30.6	2.02	3.67
Pennsylvania	I-76	3.7	51	EB	6.0	1.36	1.94
Pennsylvania	I-76	3.6	49	WB	7.7	1.78	3.29
Philadelphia	I-76	3.7	51	EB	6.0	1.36	1.94
Philadelphia	I-76	3.6	49	WB	7.7	1.78	3.29
Sacramento	US 50	6.0	69	EB	7.0	1.35	2.12
Sacramento	US 50	6.0	71	WB	7.7	1.51	2.74
Sacramento	I-80	12.4	68	EB	13.9	1.28	1.84
Sacramento	I-80	12.4	67	WB	12.1	1.09	1.31
San Diego	I-5	10.6	71	NB	9.4	1.05	1.22
San Diego	I-5	10.6	72	SB	13.1	1.47	2.45
San Diego	I-15	3.9	70	NB	4.7	1.18	2.97
San Diego	I-15	3.9	69	SB	3.8	1.14	1.50
San Francisco	I-880	4.6	71	NB	7.7	1.96	3.43
San Francisco	I-880	4.8	67	SB	5.8	1.34	1.73
San Francisco	I-680	4.2	66	NB	6.1	1.59	2.74
San Francisco	I-680	4.7	65	SB	5.0	1.15	1.25

Notes: Mean TTI = mean travel time index (mean travel time divided by free flow travel time).
 PTI = planning time index (95th percentile travel time divided by free flow travel time).
 NB = northbound, SB = southbound, EB = eastbound, WB = westbound, ES = east side, WS = west side.

Exhibit 37-7
 Freeway Reliability Values:
 Weekday P.M. Peak Period

Location	Roadway	Length (mi)	FFS (mi/h)	Direction	Avg. Travel Time (min)	Mean TTI	PTI
California	Telegraph Canyon Rd	4.4	45	EB	6.19	1.06	1.24
California	Telegraph Canyon Rd	4.4	45	WB	6.57	1.12	1.42
Delaware	US 202	3.8	42	NB	6.97	1.28	1.55
Delaware	US 202	3.9	44	SB	6.52	1.20	1.41
Maryland	Hwy 175	7.4	38	NB	13.92	1.20	1.32
Maryland	Hwy 175	7.4	38	SB	14.00	1.21	1.35
Maryland	Hwy 193	5.9	33	EB	13.75	1.26	1.45
Maryland	Hwy 193	5.9	33	WB	13.72	1.27	1.52
Maryland	Hwy 198	10.1	42	EB	16.51	1.13	1.24
Maryland	Hwy 198	10.2	41	WB	16.95	1.15	1.27
Maryland	Hwy 355	4.2	30	NB	10.37	1.23	1.38
Maryland	Hwy 355	4.2	30	SB	12.57	1.49	2.13
Maryland	Randolph Rd	6.7	35	EB	14.13	1.22	1.36
Maryland	Randolph Rd	6.7	35	WB	15.28	1.31	1.71
Maryland	US 40	4.1	41	EB	7.00	1.16	1.29
Maryland	US 40	4.2	39	WB	8.50	1.29	1.85
Pennsylvania	US 1	8.0	33	NB	19.68	1.36	1.67
Pennsylvania	US 1	7.6	32	SB	18.18	1.29	1.52
Philadelphia	Hwy 611	3.4	20	NB	13.26	1.29	1.58
Philadelphia	Hwy 611	3.3	19	SB	12.89	1.25	1.41
South Carolina	US 378	5.5	44	EB	8.61	1.16	1.29
South Carolina	US 378	5.4	45	WB	8.37	1.16	1.31

Notes: 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).
 NB = northbound, SB = southbound, EB = eastbound, WB = westbound.
 The base travel time corresponds to the 85th percentile highest speed observed during off-peak hours.

Exhibit 37-8
 Urban Street Reliability
 Values: Weekday A.M. Peak
 Period

Exhibit 37-9

Urban Street Reliability
Values: Weekday Midday
Periods

Location	Roadway	Length (mi)	FFS (mi/h)	Direction	Avg. Travel Time (min)	Mean TTI	PTI
California	Telegraph Canyon Rd	4.4	45	EB	6.27	1.07	1.23
California	Telegraph Canyon Rd	4.4	45	WB	6.46	1.10	1.28
Delaware	US 202	3.8	42	NB	7.28	1.34	1.63
Delaware	US 202	3.9	44	SB	6.93	1.28	1.47
Maryland	Hwy 175	7.4	38	NB	13.93	1.20	1.33
Maryland	Hwy 175	7.4	38	SB	14.17	1.23	1.38
Maryland	Hwy 193	5.9	33	EB	14.29	1.31	1.52
Maryland	Hwy 193	5.9	33	WB	13.99	1.29	1.49
Maryland	Hwy 198	10.1	42	EB	17.13	1.18	1.29
Maryland	Hwy 198	10.2	41	WB	17.47	1.18	1.27
Maryland	Hwy 355	4.2	30	NB	12.02	1.42	1.87
Maryland	Hwy 355	4.2	30	SB	13.07	1.55	2.01
Maryland	Randolph Rd	6.7	35	EB	14.22	1.23	1.36
Maryland	Randolph Rd	6.7	35	WB	14.62	1.25	1.42
Maryland	US 40	4.1	41	EB	7.44	1.23	1.47
Maryland	US 40	4.2	39	WB	8.01	1.22	1.42
Pennsylvania	US 1	8.0	33	NB	19.23	1.33	1.53
Pennsylvania	US 1	7.6	32	SB	19.02	1.35	1.58
Philadelphia	Hwy 611	3.4	20	NB	14.12	1.38	1.61
Philadelphia	Hwy 611	3.3	19	SB	13.78	1.34	1.63
South Carolina	US 378	5.5	44	EB	8.88	1.20	1.33
South Carolina	US 378	5.4	45	WB	8.78	1.22	1.40

Notes: 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).

NB = northbound, SB = southbound, EB = eastbound, WB = westbound.

The base travel time corresponds to the 85th percentile highest speed observed during off-peak hours.

Exhibit 37-10

Urban Street Reliability
Values: Weekday P.M. Peak
Period

Location	Roadway	Length (mi)	FFS (mi/h)	Direction	Avg. Travel Time (min)	Mean TTI	PTI
California	Telegraph Canyon Rd	4.4	45	EB	6.71	1.14	1.35
California	Telegraph Canyon Rd	4.4	45	WB	6.73	1.15	1.35
Delaware	US 202	3.8	42	NB	7.42	1.36	1.62
Delaware	US 202	3.9	44	SB	6.84	1.26	1.43
Maryland	Hwy 175	7.4	38	NB	14.20	1.23	1.36
Maryland	Hwy 175	7.4	38	SB	14.81	1.28	1.49
Maryland	Hwy 193	5.9	33	EB	16.39	1.50	1.83
Maryland	Hwy 193	5.9	33	WB	15.67	1.45	1.69
Maryland	Hwy 198	10.1	42	EB	18.53	1.27	1.50
Maryland	Hwy 198	10.2	41	WB	17.81	1.21	1.32
Maryland	Hwy 355	4.2	30	NB	14.03	1.66	2.11
Maryland	Hwy 355	4.2	30	SB	13.47	1.60	1.89
Maryland	Randolph Rd	6.7	35	EB	16.11	1.39	1.65
Maryland	Randolph Rd	6.7	35	WB	14.33	1.23	1.36
Maryland	US 40	4.1	41	EB	9.40	1.56	2.55
Maryland	US 40	4.2	39	WB	8.04	1.22	1.41
Pennsylvania	US 1	8.0	33	NB	19.63	1.36	1.53
Pennsylvania	US 1	7.6	32	SB	21.31	1.52	1.80
Philadelphia	Hwy 611	3.4	20	NB	13.22	1.29	1.48
Philadelphia	Hwy 611	3.3	19	SB	13.19	1.28	1.46
South Carolina	US 378	5.5	44	EB	9.22	1.24	1.41
South Carolina	US 378	5.4	45	WB	8.81	1.22	1.39

Notes: 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).

NB = northbound, SB = southbound, EB = eastbound, WB = westbound.

The base travel time corresponds to the 85th percentile highest speed observed during off-peak hours.

RELIABILITY STATISTICS FOR FLORIDA FREEWAYS

Exhibit 37-11 presents reliability statistics for a cross-section of Florida freeways (4). The data were gathered and reported for the p.m. peak period (4:30 p.m. to 6:00 p.m.) and are *not* aggregated over the length of the facility. The data consist of spot speeds that have been converted into travel time rates (min/mi).

The reliability statistics for Florida are reported separately from the rest of the U.S. because Florida was testing a variety of definitions of free-flow speed in the research from which these data were obtained (4). Florida usually sets the

target free-flow speed for its freeways at the posted speed limit plus 5 mi/h. However, a target speed of 10 mi/h less than the posted speed limit and a policy target speed of 40 mi/h were also being tested for reliability computation purposes. Statistics that are presented include:

- Four different TTIs (50th, 80th, 90th, and 95th percentile TTIs), based on a free-flow speed definition of the posted speed plus 5 mi/h;
- Two policy indexes, one based on the 50th percentile speed and a target speed of the posted speed minus 10 mi/h, and the other based on the 50th percentile speed and a target speed of 40 mi/h;
- A buffer time index, based on the 95th percentile speed and the mean speed; and
- A misery index based on the average of the highest 5% of travel times and a free-flow travel time based on the posted speed minus 5 mi/h.

Location	50% TTI	80% TTI	90% TTI	95% TTI (PTI)	Policy Index Alt. 1	Policy Index Alt. 2	Buffer Time Index	Misery Index
I-95 NB at NW 19th St	1.00	1.36	1.69	2.01	1.27	1.75	2.02	2.22
I-95 SB at NW 19th St	1.08	1.19	1.58	2.01	1.27	1.75	1.86	2.48
I-95 NB, S of Atlantic Blvd	1.03	1.28	1.73	2.23	1.27	1.75	2.16	2.74
I-95 SB, S of Atlantic Blvd	1.10	1.36	1.89	2.37	1.27	1.75	2.15	2.93
SR 826 NB at NW 66th St	2.40	2.82	3.07	3.35	1.33	1.50	1.39	3.69
SR 826 SB at NW 66th St	1.01	1.28	2.63	4.06	1.33	1.50	4.02	4.62
SR 826 WB, W of NW 67th Ave	1.04	1.08	1.21	1.77	1.33	1.50	1.70	2.10
SR 826 EB, W of NW 67th Ave	0.98	1.00	1.02	1.04	1.33	1.50	1.07	1.10
I-4 EB, W of World Dr	0.97	1.04	1.06	1.08	1.27	1.75	1.12	1.12
I-4 WB, W of World Dr	1.02	1.09	1.49	1.90	1.27	1.75	1.86	2.22
I-4 EB, W of Central Florida Pkwy	1.06	1.13	1.18	1.31	1.27	1.75	1.24	1.56
I-4 WB, W of Central Florida Pkwy	1.05	1.36	1.63	1.81	1.27	1.75	1.72	2.03
I-275 NB, N of MLK Jr Blvd	1.45	1.71	1.91	2.16	1.33	1.50	1.49	2.58
I-275 SB, N of MLK Jr Blvd	0.97	1.01	1.04	1.12	1.33	1.50	1.15	1.28
I-275 NB, N of Fletcher Blvd	1.05	1.07	1.11	1.21	1.33	1.50	1.16	1.35
I-275 SB, N of Fletcher Blvd	0.96	0.98	0.99	1.00	1.33	1.50	1.04	1.01
I-10 EB, E of Lane Ave	0.93	0.96	0.98	0.99	1.33	1.50	1.07	1.01
I-10 WB, E of Lane Ave	0.97	1.10	1.24	1.46	1.33	1.50	1.51	1.87
I-95 NB, S of Spring Glen Rd	1.04	1.09	1.26	1.77	1.27	1.75	1.70	2.00
I-95 SB, S of Spring Glen Rd	1.16	1.30	1.42	1.60	1.27	1.75	1.38	1.88
Minimum	0.93	0.96	0.98	0.99	1.27	1.50	1.04	1.01
Average	1.11	1.26	1.51	1.81	1.30	1.63	1.64	2.09
Maximum	2.40	2.82	3.07	4.06	1.33	1.75	4.02	4.62

Source: Adapted from Kittelson & Associates, Inc. (4).

Notes: TTI = travel time index based on the percentile speed indicated and a free-flow speed defined as (posted speed plus 5 mi/h); PTI = planning time index; Policy Index Alternative 1 = index based on the 50th percentile speed and a target speed of (posted speed minus 10 mi/h); Policy Index Alternative 2 = index based on the 50th percentile speed and a target speed of 40 mi/h; Buffer Time Index = index based on the 95th percentile and mean travel speeds; Misery Index = index based on the average of the highest 5% of travel times and a free-flow travel time based on (posted speed plus 5 mi/h).

N = north, S = south, E = east, W = west, NB = northbound, SB = southbound, EB = eastbound, WB = westbound.

Exhibit 37-11
Florida Freeway Reliability
Statistics

2. ALTERNATIVE FREEWAY INCIDENT PREDICTION METHOD

As discussed in the Data Acquisition section of Chapter 36, Travel Time Reliability, it is only possible to estimate freeway incident probabilities directly in the rare cases where incident logs are complete and accurate over the entire reliability reporting period. On the other hand, data on the number of crashes on a specific facility or specific type of facility (e.g., all freeways in a region) is usually obtainable. This section presents a method for estimating facility incident probabilities from a known or predicted crash rate, based on an assumption that the number of incidents in a given study period is Poisson distributed (5, 6).

Equation 37-1 estimates the expected number of incidents n_j during the study period under a given demand pattern j as a function of the facility's crash rate, the ratio of incidents to crashes, the traffic demand, and the facility length:

Equation 37-1

$$n_j = CR \times ICR \times (AADT \times 10^{-8} \times D \times \frac{DR_j}{DM} \times K_s) \times L_f$$

where

n_j = Expected number of incidents during the study period under demand pattern j ,

CR = Local (facility or regional freeway) crash rate per 100 million vehicle-miles traveled (VMT) (crashes/100 million VMT),

ICR = Local incident-to-crash ratio (unitless),

$AADT$ = Annual average daily traffic (veh),

D = Directional distribution of traffic demand (decimal),

DR_j = Demand ratio for demand pattern j (unitless),

DM = Demand multiplier (pattern independent) (unitless),

K_s = Proportion of daily demand volume that occurs during the study period (pattern independent), and

L_f = Facility length (mi).

The arrival of vehicles involved in an incident is assumed to follow the Poisson distribution. Thus, the probability $P_j(X)$ of X incidents in demand pattern j , with an expected number of incidents n_j during the study period under demand pattern j , is estimated from:

Equation 37-2

$$P_j(X) = \frac{n_j^X}{X!} e^{-n_j}$$

The probability of having *no* incidents occur in demand pattern j is then simply:

Equation 37-3

$$P_j(0) = \frac{n_j^0}{0!} e^{-n_j} = e^{-n_j}$$

Finally, the probability of having *at least one* incident occur in demand pattern j is one minus the probability of having no incidents:

$$P_j(> 0) = 1 - P(0) = 1 - e^{-n_j}$$

Equation 37-4

Estimating the probability of the occurrence of a specific incident type i requires data on the fraction of all incidents that are of that type and their average duration. These can be determined from local data or, in the absence of such data; the national default values given in Chapter 36 can be applied. The overall duration of a given incident type i is computed by weighting the probability of incident type i by its expected duration, recognizing from Equation 37-1 that the incident probability is linearly correlated with traffic demand. Since the units for the number of incidents X are based on the study period, the incident duration must also be expressed in the same unit of study period (e.g., minutes or hours).

If g_i is the proportion of all incidents that are of type i , t_{SP} is the study period duration (minutes or hours), and t_E is the average incident event duration (minutes or hours), then the time-based probability of at least one incident of type i in demand pattern j is:

$$P_{i,j} = 1 - e^{-(n_j g_i)(t_E/t_{SP})}$$

Equation 37-5

Repeating the computation of Equation 37-5 for all combinations of incident types and demand patterns allows the development of the incident probability matrix that is required as an input to the freeway reliability method.

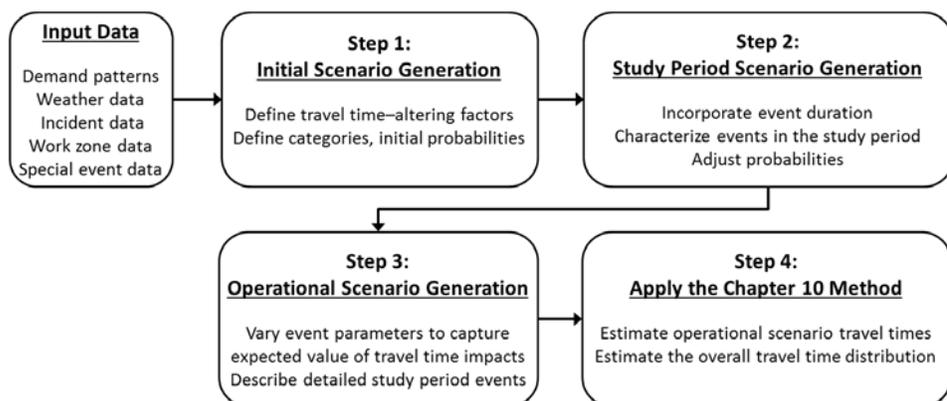
3. FREEWAY SCENARIO GENERATION

INTRODUCTION

This section provides details of the freeway scenario generation process. An overview of this process is provided in Chapter 36, Travel Time Reliability.

Freeway scenario generation is a deterministic process. This deterministic approach enumerates different operational conditions of a freeway facility based on different combinations of factors which affect travel time. Each unique set of operational conditions forms a *scenario*. Four principal steps are involved in the scenario generation process, as shown in Exhibit 37-12.

Exhibit 37-12
Process Flow Overview for
Freeway Scenario Generation



Scenario generation can work both in data-rich and data-poor environments, as well as anywhere in between. In a data-rich environment, the analyst uses local data as much as possible. In a data-poor setting, the analyst relies on national default values to generate the scenarios. At a minimum, however, the analyst must provide facility AADT, geographic location, and detailed geometric data, much as he or she already would for a *Highway Capacity Manual* (HCM) operations analysis.

INITIAL SCENARIO GENERATION

The freeway scenario generator generates and assigns initial probabilities to a number of *initial scenarios*, combinations of events that occur within a given time period, such as a weekday or, more likely, a few hours thereof. An initial scenario's probability is expressed as the fraction of time a particular combination of events (e.g., demand, weather, incidents) take place during the study period of interest.

Initial scenario probabilities are computed assuming independence between events. During this stage of scenario generation, the probabilities do not take into account the actual duration of the event in question. They only account for the categories of weather or incidents. Therefore, the initial probabilities must be adjusted to account for actual event durations; in some cases, the event durations themselves must be adjusted. The rationale for making these adjustments is described later in detail in the Motivation Using a Simple Example subsection.

Assumptions

The following assumptions are made in generating initial scenarios:

- The contributing factors to the travel time variation are independent. The method provides the ability to vary some factors (e.g., demand by weather type), but not until later in the process, when operational scenarios are generated.
- Each factor that contributes to travel time variability is categorized into discrete categories with time-wise probabilities of occurrence (not frequencies or chance of occurrence). If local probabilities are not available, alternative methodologies are used (e.g., application of default values) to estimate those probabilities.
- The time unit for scenario generation is minutes. Every calculation for measuring probability is based on minutes. However, any other time unit can be used and expressed as a fractional number.
- Any time instance in the study period or reliability reporting period is independent of other time instances.

Required Input Data

This subsection describes the data required to calculate an initial scenario's probabilities. In general, the time-wise probabilities of all the various types of events contributing to travel time variation should be known. Incident and weather probabilities do not deal with the frequency or counts of those events. Instead, event frequencies are estimated from given time-wise probabilities and expected durations of different types of events.

Demand Variability

Demand is categorized by defining demand patterns within the reliability reporting period. Days with similar demand levels are assigned to a single demand pattern. The basis for defining demand patterns consists of two dimensions, accounting for month-of-year and day-of-week demand variability within the reliability reporting period. Monthly variability usually reflects seasonal demand effects, while day-of-week variability reflects the effect of daily variation in demand levels.

Demand ratios must be provided for each combination of weekday (up to 7 days) and month (up to 12 months) within the reliability reporting period (up to 84 total values). The demand ratios are expressed as the ADT for a given day-month combination relative to either (a) a specific day-month combination or (b) AADT. In addition, a *demand multiplier* must be provided, defined as the demand ratio for the base dataset's demand. If the base dataset's demands are reflective of AADT and the supplied demand ratios are relative to AADT, for example, the demand multiplier will be 1.00.

Once the demand ratios have been developed, the analyst can optionally define demand patterns based on combinations of days and months with similar demand ratios (e.g., Mondays, Tuesdays, and Wednesdays in summer months). The use of demand patterns reduces the number of scenarios that are ultimately

generated, which directly impacts the time required to perform a reliability analysis.

The probability of a given demand pattern d is the portion of the reliability reporting period $P_{DP}(d)$ represented by the demand pattern (in minutes), divided by the total number of study period (SP) minutes in the reliability reporting period (RRP):

$$\text{Equation 37-6} \quad P_{DP}(d) = \frac{\text{Sum of SP minutes within demand pattern } d}{\text{Sum of SP minutes in RRP}}$$

For example, if a demand pattern consists of Thursdays in March, April, and May; the study period is defined as 6 h; and the reliability reporting period is defined as all weekdays in a year (261 days), then the probability of occurrence of this demand pattern is:

$$P_{DP} = \frac{(13 \text{ weeks}) \times (1 \text{ day}) \times (6 \text{ h/day}) \times (60 \text{ min/h})}{(261 \text{ days}) \times (6 \text{ h/day}) \times (60 \text{ min/h})} = 4.98\%$$

Weather Variability

Chapter 10, Freeway Facilities, provides 15 categories of weather events that influence freeway capacity. Five of these categories have a negligible (<4%) effect on freeway capacity and are therefore not addressed further in the reliability methodology. The remaining 10 *severe weather* categories, plus a non-severe weather category are considered, as shown in Exhibit 36-4. The probability of each of these 11 weather events must be provided for each month within the reliability reporting period (up to 12 months), resulting in a total of up to 132 values.

In data-rich environments where agencies have access to detailed local weather data, the probability $P_W(w,m)$ of weather type w in month m is computed based on Equation 37-7. Weather types are mutually exclusive, so when two or more categories may be identified for the same time period (i.e., low visibility and heavy rain) the time is assigned to the category with largest capacity effect.

$$\text{Equation 37-7} \quad P_W(w,m) = \frac{\text{Sum of SP durations in month } m \text{ with weather type } w \text{ (min)}}{\text{Sum of all SP durations in month } m \text{ (min)}}$$

The method provides the analyst with the option of removing weather events with very low probabilities so as to reduce the overall number of scenarios. Any weather event with a probability lower than the analyst-specified threshold is removed and its probability is assigned to the remaining weather events in proportion to their probabilities. It is not recommended to use a large value for this threshold, since it can introduce bias and shift the resulting travel time distribution.

Incident Variability

Incidents are categorized based on their capacity impacts. Six incident types are defined: no incident, shoulder closure only, and 1-, 2-, 3-, and 4-lane closures. The probability $P_{INC}(i,m)$ of incident type i occurring in month m is:

$$\text{Equation 37-8} \quad P_{INC}(i,m) = \frac{\text{Sum of SP durations in month } m \text{ with incident type } i \text{ (min)}}{\text{Sum of all SP durations in month } m \text{ (min)}}$$

If local incident probabilities are not available for a facility, then local crash rates or crash rates predicted from the HERS model (7) can be used along with an incident-to-crash ratio to calculate the probabilities of different incident types. This process was described in Section 2, Alternative Freeway Incident Prediction Method.

Independence of Time Instances and Joint Events

The event probabilities provided as input data reflect the frequency of an event occurrence during a specified time period (e.g., heavy snow in January). However, the scenario generator computes *time-wise probabilities* of an event—the chance of exposure to a specific event during any minute within a study period or the reliability reporting period. From a mathematical perspective, the duration of weather and incident events is not considered in the initial scenario generation step. Any minute within a study period or reliability reporting period is therefore assumed to be independent of any other minute. More precisely, if the state of any event in any minute is known, it has no impact on the probability of encountering any other event in any other minute.

One basic assumption is that all contributing factors to travel time variation are independent. As such, the probability of an initial scenario is the product of the probabilities of all contributing factors. For example, there is no dependency between certain demand levels and different weather types. The freeway reliability method combines these categories and multiplies their probabilities to generate the different operational conditions of the freeway facility that are known as initial scenarios.

Equation 37-9 demonstrates the joint probability of a particular initial scenario based on the probability of scenario's weather and incident conditions, considering independence between factors.

$$P\{\text{demand pattern } d, \text{ weather type } w, \text{ incident type } i\} = \\ P\{\text{demand pattern } d\} \times P\{\text{weather type } w\} \times P\{\text{incident type } i\} = \\ P_{DP}(d) \times P_w^{DP}(d, w) \times P_{INC}^{DP}(d, i)$$

Equation 37-9

It is important to note that some dependencies between different types of events are inherent through the use of the calendar. For example, both demand levels and weather conditions are associated with the calendar; therefore, a correlational (not a causal) relationship exists between the two factors. Incident probabilities are also tied to the prevailing demand levels, again providing a correlation through the calendar. The analyst can provide specific monthly crash or incident rates to the scenario generator to express further association between weather and incident probabilities.

Aggregation of Probabilities Across Demand Patterns

An initial scenario is characterized by its demand pattern, weather, and incident type. The scenario's probability can be computed from Equation 37-9. However, the probability of weather and incidents are provided as monthly values, while demand is categorized based on a demand pattern definition which is often not monthly. Thus, the probabilities of weather and incidents must be aggregated across the various demand patterns. The demand pattern dependent

probabilities of weather $P_W^{DP}(w,m)$ for weather type w in month m , and of incidents $P_{INC}^{DP}(i,m)$ of type i in month m , for demand pattern d are computed from Equation 37-10 and Equation 37-11 respectively.

Equation 37-10

$$P_W^{DP}(d,w) = \frac{\sum_{\forall m \in DP} P_W(w,m) \times N_{DP}(d,m)}{\sum_{\forall m \in DP} N_{DP}(d,m)}$$

Equation 37-11

$$P_{INC}^{DP}(d,i) = \frac{\sum_{\forall m \in DP} P_{INC}(i,m) \times N_{DP}(d,m)}{\sum_{\forall m \in DP} N_{DP}(d,m)}$$

where $N_{DP}(d,m)$ denotes the number of days in demand pattern d occurring in month m in the RRP and other variables are as defined previously.

An initial scenario describes the operational condition of the freeway facility and the probability associated with it. This probability is the expected portion of time that the freeway facility is subject to operate at the conditions specified for the scenario. Thus, each initial scenario presents an expected travel time and its associated probability. By modeling these scenarios and measuring their travel times, a discrete distribution of expected travel times is generated, which can subsequently be used to assess the freeway facility's reliability.

STUDY PERIOD SCENARIO GENERATION

While the initial scenarios describe the general conditions under which a facility will operate (e.g., a weather event will occur sometime during the study period, an incident will take place sometime and somewhere on the facility), they lack the specificity that allows an event's effect on facility performance on a given day to be evaluated.

Study period scenarios specify event time durations and the corresponding adjustments to initial scenario probabilities. Each initial scenario has a unique study period associated with it. The only difference between an initial scenario and a study period scenario is the probability associated with each one. This subsection describes the computations required to achieve this transition.

Motivation Using a Simple Example

Facility Description

Consider a freeway facility consisting of 10 HCM segments. The reliability reporting period contains 50 workday Fridays, each of which has the same demand pattern. The study period is 3 p.m. to 7 p.m., resulting in sixteen 15-min analysis periods.

For simplicity, one severe weather condition and one incident are considered in the reliability reporting period: medium rain with a total duration of 600 min in the reliability reporting period and one lane closure with a total duration of 900 min in the reliability reporting period. Exhibit 37-13 summarizes these conditions with respect to their time-wise probabilities.

The time-wise probability expresses how likely an event will occur in any time instance during the reliability reporting period. This probability translates into any time period that one can report. For example, if the duration of the study period is 4 h, then it is expected that the event will be present for a period of time equal to its probability times the study period duration. The term "time-

wise” distinguishes it from other types of probabilities, such as VMT-wise, count-wise, or length-wise probabilities.

Event	Time-Wise Probability of Occurrence
WEATHER EVENT	
Medium rain	$\frac{600 \text{ min duration}}{50 \text{ study periods} \times 4 \text{ h/study period} \times 60 \text{ min/h}} = 0.05$
Non-severe weather	$1 - 0.05 = 0.95$
INCIDENT EVENT	
One-lane closure	$\frac{900 \text{ min duration}}{50 \text{ study periods} \times 4 \text{ h/study period} \times 60 \text{ min/h}} = 0.075$
No Incident	$1 - 0.075 = 0.925$

Exhibit 37-13
Example Time-wise
Probabilities of Event
Occurrences

Initial Scenario Development

The initial scenario generation procedure is employed to generate different operational conditions on the freeway facility. These conditions are assumed to be independent. Exhibit 37-14 summarizes the operational conditions associated with the initial scenarios in this example.

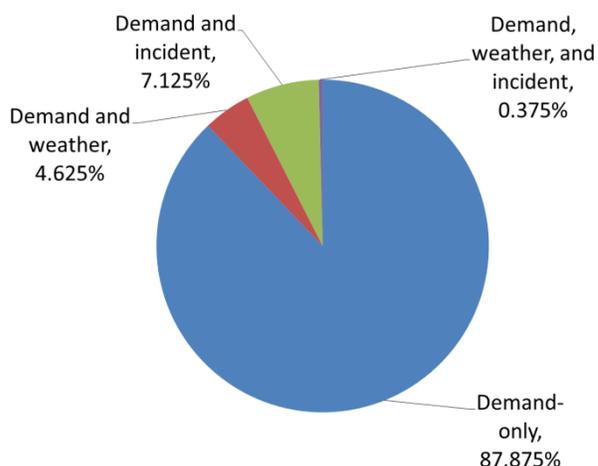
Initial Scenario Number	Weather Condition	Incident Condition	Initial Scenario Description	Probability
1	Non-severe	No incident	Demand-only	$P_1 = 0.95 \times 0.925 = 0.87875$
2	Medium rain	No incident	Demand and weather	$P_2 = 0.05 \times 0.925 = 0.04625$
3	Non-severe	1 lane closed	Demand and incident	$P_3 = 0.95 \times 0.075 = 0.07125$
4	Medium rain	1 lane closed	Demand, weather, and incident	$P_4 = 0.05 \times 0.075 = 0.00375$
Sum=1				

Exhibit 37-14
Example Initial Scenarios

The initial scenarios in the above form are not ready to be provided to the HCM Chapter 10 methodology, since they do not contain any of the critical event attributes that impact travel time (e.g., location, duration, start time).

The joint probabilities of these operational conditions are time-wise as well. If any time instance across all study periods in the reliability reporting period is chosen, it will yield a non-severe-weather and no-incident condition (Demand-Only scenario) with a probability of almost 88%. Exhibit 37-15 depicts the probabilities associated with each initial scenario.

Exhibit 37-15
Distribution of Initial Scenario
Categories



Study Period Scenario Development

Next, the event durations are introduced. Based on historical data, the average durations are 49 min and 32 min for the one-lane closure incident and the medium rain event, respectively. Because the Chapter 10 freeway facilities method uses 15-min analysis periods, these average durations are rounded to 45 and 30 min, respectively (three and two analysis periods, respectively).

To accommodate the four combinations of weather and incident events being modeled, four study period scenarios are defined. Modeling these four study periods guarantees that all the operational condition characteristics are accounted for at the correct time-wise probabilities. A weight (or probability), the *study period scenario probability*, is assigned to these study periods to be fully consistent with the specified likelihood of the operational conditions (initial scenarios).

The objective now is to determine what weight to give to each of the four study period scenarios so that the resulting travel time distribution represents the facility's prespecified operational conditions of the facility. In other words, considering the initial scenario probability values $P_1, P_2, P_3,$ and P_4 and the respective durations of the events and the study period, what should be the study period scenario probability values $\pi_1, \pi_2, \pi_3,$ and π_4 that would provide consistent time-based probabilities throughout? *The study period scenario probabilities should be selected in a way that the likelihood of the conditions modeled are identical to the initial scenario probabilities.*

To achieve this result, the equalities given below must be satisfied, covering each of the initial scenarios. The logic behind each equation is to equalize the proportion of time each study period scenario should be represented, based on the initial scenario probabilities, recognizing that there are periods of no-incident or no-severe weather conditions in all four study periods.

For example, in study period scenario 2 (medium rain and no incident), severe weather occurs in 2 of the 16 analysis periods, meaning that no-incident and no-severe-weather conditions are present in the remaining 14 analysis periods. Similarly, in study period scenario 3 (non-severe weather and a 1-lane-closure incident), the incident is present in 3 of the 16 analysis periods and no-

event conditions are present in the remaining 13 analysis periods. Finally, in study period scenario 4 (medium rain and a 1-lane-closure incident), the longer of the two durations (in this case, 3 analysis periods) determines when any event is present, while the shorter of the two durations (in this case, 2 analysis periods) determines how long the combined weather and incident condition occurs.

Equation 37-12 provides the equality relationship for initial scenario 1, representing a demand-only condition. The probability of this scenario must equal the combined probabilities of the demand-only portions of the four study period scenarios.

$$P_1 = \left(\frac{16-0}{16}\right)\pi_1 + \left(\frac{16-2}{16}\right)\pi_2 + \left(\frac{16-3}{16}\right)\pi_3 + \left(\frac{16-3}{16}\right)\pi_4$$

Equation 37-12

Study period scenario 1 has 16 demand-only analysis periods out of 16 total analysis periods; study period scenario 2 has 14 such analysis periods out of 16, and so on. The proportion of demand-only analysis periods in each study period scenario is multiplied by that scenario's probability π_i .

Equation 37-13 provides the equality relationship for initial scenario 2, representing a combined demand and severe weather event condition. This condition does not occur at all in study period scenarios 1, 3, or 4, and only occurs during 2 of the 16 analysis periods during study period 2. Therefore:

$$P_2 = \left(\frac{2}{16}\right)\pi_2$$

Equation 37-13

Similarly, a combined demand and incident condition occurs during 3 of the 16 analysis periods in study period scenario 3 and in 1 of the 16 analysis periods in study period scenario 4. A combined demand, weather, and incident condition occurs only during 2 of the 16 analysis periods in study period scenario 4. Equation 37-17 and Equation 37-185 give the respective equality relationships for initial scenarios 3 and 4.

$$P_3 = \left(\frac{3}{16}\right)\pi_3 + \left(\frac{1}{16}\right)\pi_4$$

Equation 37-14

$$P_4 = \left(\frac{2}{16}\right)\pi_4$$

Equation 37-15

With four equations and four unknowns, the four equations above can be solved for the various π_i values, yielding the following results:

$$\pi_1 = 0.23; \pi_2 = 0.37; \pi_3 = 0.37; \text{ and } \pi_4 = 0.03.$$

By assigning these π_i values to the four specified study period scenarios, the resulting travel time distribution will yield facility travel times consistent with the intended distribution of the operational conditions.

Note the large difference between P_1 (88%) and π_1 (23%). This does not mean that normal conditions have been reduced by this amount in the study period scenarios. It is simply reflective of the fact that "pieces" of P_1 exist in all four study period scenarios, as indicated in the first of the four equilibrium equations above. Similarly, the large disparity between P_2 and π_2 , and between P_3 and π_3 is explained by the fact that these two study period scenarios also contain many non-incident, non-severe-weather analysis periods.

The large difference in P_1 and π_1 values reflects that pieces of the no-incident, non-severe-weather initial scenario exist in all four study period scenarios.

It is possible that the set of equilibrium equations could yield infeasible results (meaning that one of the resulting π_i values is negative). This could occur if the likelihood of the weather or incident event is high, and the expected event duration is short. In these cases, the duration of the event should be increased, or more than one event per study period should be modeled.

Operational Scenario Development

The final step in the scenario generation process is to develop the operational scenarios. There are two possible start times for weather events, along with three possible start times, three possible durations, and two possible locations for incidents. Each possible combination is assumed to occur with equal probability.

Exhibit 37-19 depicts one possible operational scenario in each of the four study periods associated with a study period scenario. Each study period is 4 h (or 16 analysis periods) long, consistent with the specified duration. The exhibit shows the expected duration and location of the weather and incident events associated with the operational scenarios.

At this point, sufficient information is available to model the facility using the Chapter 10 freeway facilities method, as the weather and incident events have been fully specified in terms of their start time, duration, and affected segments. In addition, the probabilities of each operational scenario have been determined, allowing the resulting travel time distribution to be properly aggregated.

Scenario 1	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 7	Segment 8	Segment 9	Segment 10
t=1										
t=2										
t=3										
t=4										
t=5										
t=6										
t=7										
t=8										
t=9										
t=10										
t=11										
t=12										
t=13										
t=14										
t=15										
t=16										

Scenario 2	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 7	Segment 8	Segment 9	Segment 10
t=1										
t=2										
t=3										
t=4										
t=5										
t=6										
t=7										
t=8										
t=9										
t=10										
t=11										
t=12										
t=13										
t=14										
t=15										
t=16										

Operational Scenario Probability = π_1

Operational Scenario Probability = $\pi_2 / 2$

Scenario 3	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 7	Segment 8	Segment 9	Segment 10
t=1										
t=2										
t=3										
t=4										
t=5										
t=6										
t=7										
t=8										
t=9										
t=10										
t=11										
t=12										
t=13										
t=14										
t=15										
t=16										

Scenario 4	Segment 1	Segment 2	Segment 3	Segment 4	Segment 5	Segment 6	Segment 7	Segment 8	Segment 9	Segment 10
t=1										
t=2										
t=3										
t=4										
t=5										
t=6										
t=7										
t=8										
t=9										
t=10										
t=11										
t=12										
t=13										
t=14										
t=15										
t=16										

Operational Scenario Probability = $\pi_3 / 18$

Operational Scenario Probability = $\pi_4 / 18$

Demand	Demand and weather	Demand and incident	Demand, weather, and incident
--------	--------------------	---------------------	-------------------------------

Exhibit 37-16
Events Occurring During Each Analysis Period of Selected Operational Scenarios

Algorithm Assumptions

The following assumptions are incorporated into the algorithm for developing study period scenario probabilities:

- The duration of incident events may be altered in the development of the operational scenarios later in the process without altering the study period probabilities. This assumption is not overly severe, since the three possible incident durations are selected to be at, below, and above the mean duration.
- All events are rounded to the nearest 15-min increment. This process potentially introduces some errors and bias to the reliability calculations; however, the method accounts for this bias and eliminates its effects.

Scenario Categories

Scenarios are divided into four categories:

1. Demand-only scenarios (normal condition),
2. Demand with weather scenarios,
3. Demand with incident scenarios, and
4. Demand with weather and incident scenarios.

This categorization is needed to execute the probability adjustment procedure when generating study period scenarios. Typically, the demand-only category has a high probability of occurrence. Demand patterns are modeled using the demand ratios. Each scenario (initial, study period, or operational) has an associated demand multiplier which applies to all segments and time periods.

In order to model the impacts of weather and incident events, appropriate Capacity Adjustment Factors (CAFs) and Free Flow Speed Adjustment Factors (SAFs) are applied to the impacted segments and time periods. For incidents, the number of open lanes is also adjusted based on the type of incident.

Subsets of Initial Scenarios

In a facility with N demand patterns, all initial scenarios could be divided into N subsets. These subsets are mutually exclusive and their union covers all initial scenarios. The methodology for adjusting the probabilities of study period scenarios applies to each subset separately.

Exhibit 37-17 presents an example of one such subset associated with one specific demand pattern that has a probability of occurrence of 14.18%.

Initial Scenario #	Demand Pattern	Weather Type	Incident Type	Initial Scenario Probability	Scenario Category
4	1	Normal weather	No incident	8.84736%	1
16	1	Normal weather	Shoulder closed	3.00484%	3
28	1	Normal weather	1 lane closed	0.90935%	3
29	1	Light snow	No incident	0.44710%	2
42	1	Normal weather	2 lanes closed	0.23029%	3
45	1	Normal weather	3 lanes closed	0.18409%	3
48	1	Light snow	Shoulder closed	0.14825%	4
49	1	Medium rain	No incident	0.14309%	2
68	1	Low visibility	No incident	0.06633%	2
74	1	Medium rain	Shoulder closed	0.05025%	4
77	1	Light snow	1 lane closed	0.04479%	4
88	1	Low visibility	Shoulder closed	0.02332%	4
96	1	Light-medium snow	No incident	0.01666%	2
99	1	Medium rain	1 lane closed	0.01524%	4
104	1	Light snow	2 lanes closed	0.01134%	4
117	1	Light snow	3 lanes closed	0.00906%	4
120	1	Low visibility	1 lane closed	0.00707%	4
128	1	Light-medium snow	Shoulder closed	0.00531%	4
138	1	Medium rain	2 lanes closed	0.00386%	4
146	1	Medium rain	3 lanes closed	0.00309%	4
163	1	Low visibility	2 lanes closed	0.00179%	4
164	1	Light-medium snow	1 lane closed	0.00160%	4
166	1	Low visibility	3 lanes closed	0.00143%	4
203	1	Light-medium snow	2 lanes closed	0.00040%	4
209	1	Light-medium snow	3 lanes closed	0.00032%	4

Exhibit 37-17
Example Subset of Initial Scenarios Associated with a Demand Pattern

Conceptual Approach

The study period probability adjustment method creates weather or incident events in the study period with a predetermined duration. Thus, the remaining time periods in that study period actually describe another scenario (usually the normal condition, scenario category 1). Therefore, each study period scenario is in fact associated with more than one initial scenario.

Exhibit 37-18 depicts an example where a study period scenario contains three initial scenario categories: demand-only (during $t_{1,1}$ and $t_{1,2}$), demand with weather (during $t_{2,1}$), and demand with weather and incident (during $t_{4,1}$).

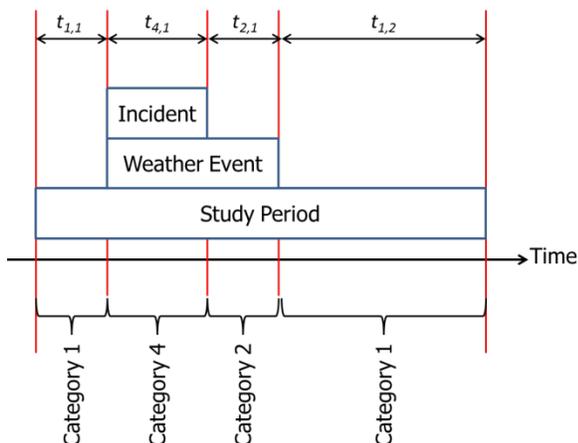


Exhibit 37-18
Example Study Period with Incident and Weather Events

Equation 37-16

If the probability of occurrence of a study period is given as Π , then the probability of occurrence $P(s)$ of a particular scenario category s that appears i times within the study period with individual durations $t_{s,i}$ is as follows

$$P(s) = \Pi \times \left(\frac{\sum_i t_{s,i}}{t_{SP}} \right)$$

where t_{SP} is the study period duration in minutes.

For the situation depicted in Exhibit 37-18, the study period scenario probabilities are:

$$P(1) = \Pi \times \left(\frac{t_{1,1} + t_{1,2}}{t_{SP}} \right)$$

$$P(2) = \Pi \times \left(\frac{t_{2,1}}{t_{SP}} \right)$$

$$P(3) = 0$$

$$P(4) = \Pi \times \left(\frac{t_{4,1}}{t_{SP}} \right)$$

As shown in the above equations, there is a one-to-one relationship between the initial and study period scenario probabilities. The initial scenario probabilities are known and the study period probabilities Π are calculated.

Study Period Scenario Probability Calculation

Calculating the probability of a study period scenario requires 10 steps. For some combinations of event durations and study period durations, the method may generate negative probabilities for study period scenarios. Steps 4, 6, and 9 of the method overcome this infeasibility by increasing the number (essentially the duration) of events in the study period to generate a feasible solution. Exhibit 37-19 shows the process flow of the proposed methodology.

Step 1: Select Initial Scenarios Associated with a Specific Demand Pattern

In this step, all combinations of weather and incident types associated with a given demand pattern are selected. The normal condition scenario typically has a large probability of occurrence relative to the other scenarios.

For example, the sample data in Exhibit 37-17 show five weather types (normal, medium rain, low visibility, light snow, and light-medium snow) and five incident types (no incident, shoulder closed, one lane closed, two lanes closed, and three lanes closed) associated with a given demand pattern. Exhibit 37-20 summarizes the probability of each of the combinations in the sample data. The sum of the probabilities of all of the initial scenarios is 14.176%. Therefore, the sum of the adjusted probabilities for the study period scenarios must also be 14.176%.

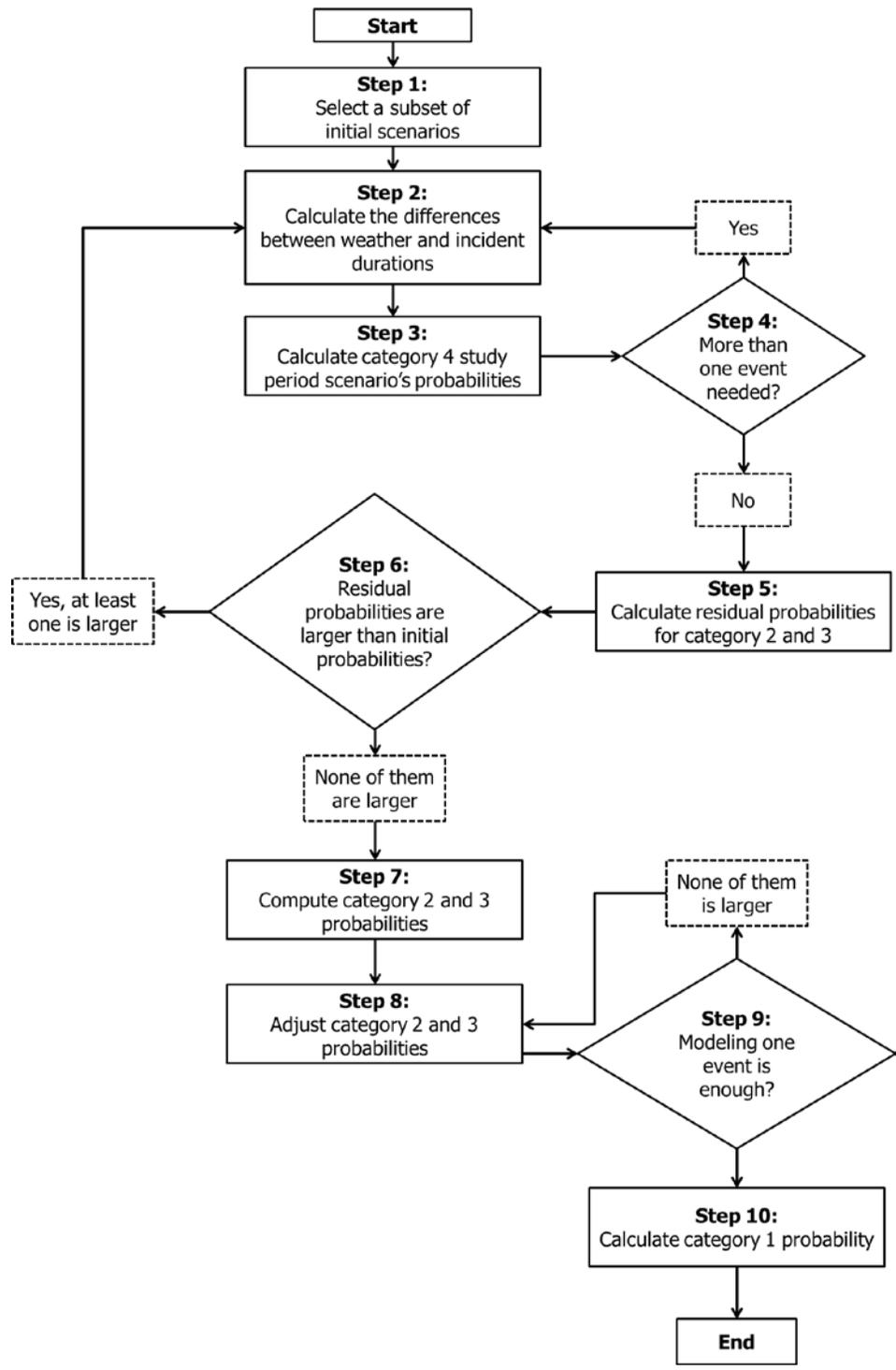


Exhibit 37-19
Probability Calculation
Methodology for Study Period
Scenarios

Exhibit 37-20

Example Combinations of Weather and Incidents Associated with a Demand Pattern

Incident Categories <i>I</i>	Weather Categories <i>w</i>					Total
	Normal	Medium Rain	Low Visibility	Light-Med. Snow	Light Snow	
No incident	8.84737%	0.14309%	0.06633%	0.01666%	0.44710%	9.52054%
Shoulder closed	3.00484%	0.05025%	0.02332%	0.00531%	0.14825%	3.23197%
1 lane closed	0.90935%	0.01524%	0.00707%	0.00160%	0.04479%	0.97805%
2 lanes closed	0.23029%	0.00386%	0.00179%	0.00040%	0.01134%	0.24769%
3 lanes closed	0.18409%	0.00309%	0.00143%	0.00032%	0.00906%	0.19799%
Total	13.17593%	0.21553%	0.09995%	0.02430%	0.66053%	14.17625%

Note: Med. = Medium.

Step 2: Calculate Time Differences Between Weather and Incident Event Durations

According to the definition of category 4 initial scenarios (demand with weather and incidents), the effect of weather and incidents applies to the freeway facility with the same duration. In reality, they might have different durations. Therefore, this step compares the durations of weather and incident events and calculates the differences.

Modeling any weather or incident event requires its duration to be rounded to the length of the nearest analysis period length, or 15 min. The notation $\text{Round}(t)$ is used to symbolize the rounded value of t to its nearest 15-min value.

The time that both weather and incident events occur ω_{wi} and the difference in weather and incident durations Δ_{wi} are calculated as follows for each category 4 scenario:

Equation 37-17

$$\omega_{wi} = \text{Min} \left(\text{Round}(\tau_w^{wea}), \text{Round}(\tau_i^{inc}) \right)$$

Equation 37-18

$$\Delta_{wi} = \left| \text{Round}(\tau_w^{wea}) - \text{Round}(\tau_i^{inc}) \right|$$

where

ω_{wi} = time that both weather events w and incident event i occur in a category 4 initial scenario (min),

Δ_{wi} = difference in duration between weather event w and incident event i (min),

τ_w^{wea} = duration of weather event w (min), and

τ_i^{inc} = duration of incident event i (min).

Step 3: Calculate Category 4 Study Period Scenario Probability

If only a single weather event coincides with a single incident event in a study period scenario, then the relationship between the study period scenario's probability π_{wi} and the initial scenario's probability P_{wi} is in the form of

Equation 37-19

$$P_{wi} = \pi_{wi} \times \left(\frac{\omega_{wi}}{t_{SP}} \right)$$

where t_{SP} is the study period duration in minutes.

This equation shows a one-to-one relationship between study period and initial scenario probabilities. It indicates that the probability of an initial scenario is the proportion of time that has the same condition during the study period, multiplied by the probability of the study period scenario. Although the condition immediately after the event is not completely the same as the normal

condition scenario (category 1)—for example, the impact of wet pavement after a rain event has ended—that effect is ignored in the method. This bias is considered negligible. Equation 37-20 gives the probability of the study period scenarios as a function of the probability of the initial scenarios, where all variables are as previously defined.

$$\pi_{wi} = P_{wi} \times \left(\frac{t_{SP}}{\omega_{wi}} \right)$$

Equation 37-20

Step 4: Check Necessity for Modeling More Than One Event in Category 4 Scenarios

The sum of all probabilities generated in Step 3 for category 4 scenarios should be less than the sum of the initial scenario probabilities. Otherwise, the study period scenarios would need more than one event per study period. Equation 37-21 provides a check for proceeding to Step 5 with no change in event durations:

$$\sum_{\substack{w=1 \text{ to } 10 \\ i=1 \text{ to } 5}} \pi_{wi} < \sum_{\substack{w=0 \text{ to } 10 \\ i=0 \text{ to } 5}} P_{wi}$$

Equation 37-21

where w and i represent the weather and incident types, respectively, j is the number of weather types represented in a category 4 study period scenario, and an index value of 0 represents the no-event condition (i.e., non-severe weather or no incident).

Should the constraint in Equation 37-21 not be met, the solution lies in modeling more than one incident and weather event simultaneously. Therefore the process of modeling more than one event should be followed (i.e., increase the values of ω_{wi}), and Steps 2 and 3 should be repeated to make sure that the sum of all probabilities is low enough that the condition in Equation 37-21 is satisfied. Differences between weather and incident event durations should also be investigated. In some cases, repeating the shorter event (usually the incident) satisfies the condition, thus modeling two incidents concurrent with one weather event. If any such changes are made, Steps 2 and 3 should be repeated.

Step 5: Calculate Residual Probabilities for Category 2 and 3 Scenarios

Residual probabilities are imposed by the differences in durations of the weather and incident events in category 4 scenarios. In Step 3, the study period was modeled with weather and incident events together with common durations and probabilities. Because weather and incident events are likely to have different durations, the effect of the longer of the two events should be modeled to maintain accuracy.

Category 4 scenarios can be divided into three groups:

- Type *W* scenarios where the rounded weather event duration is greater than the rounded incident event duration,
- Type *I* scenarios where the rounded incident event duration is greater than the rounded weather event duration, and
- Type *N* scenarios where the rounded weather and incident event durations are equal.

There is no need to compute the residual probabilities for type N scenarios; therefore the remainder of this step focuses on type W and I scenarios.

In this step a portion of the probability of each demand-plus-weather scenario (category 2) is assigned to the type W scenarios, and a portion of the probability of demand-plus-incident (category 3) scenarios is assigned to the type I scenarios. This is because the study period scenarios generated in step 3 not only represent category 4 scenarios, but portions of them also represent category 2 or 3 scenarios (or both).

The probability residual of category 4 scenarios assigned to category 2 scenarios π'_w is calculated as follows:

Equation 37-22

$$\pi'_w = \sum_{i=1}^5 \pi_{wi} \times \alpha_{wi} \times \left(\frac{\Delta_{wi}}{t_{SP}} \right)$$

where

π'_w = probability residual of category 4 scenarios assigned to category 2 scenarios;

π_{wi} = probability of study period scenario with weather type w and incident type i ;

α_{wi} = 1, for type W scenarios, and 0 otherwise;

Δ_{wi} = difference in duration between weather event w and incident event i (min); and

t_{SP} = study period duration (min).

Similarly, the probability residual of category 4 scenarios assigned to category 3 scenarios π''_i is calculated as follows:

Equation 37-23

$$\pi''_i = \sum_{w=1}^{10} \pi_{wi} \times \beta_{wi} \times \left(\frac{\Delta_{wi}}{t_{SP}} \right)$$

where

π''_i = probability residual of category 4 scenarios assigned to category 3 scenarios;

π_{wi} = probability of study period scenario with weather type w and incident type i ;

β_{wi} = 1, for type I scenarios, and 0 otherwise;

Δ_{wi} = difference in duration between weather event w and incident event i (min); and

t_{SP} = study period duration (min).

The α_{wi} and β_{wi} indicator variables are used to filter the type W and I scenarios.

Step 6: Check that Residual Probabilities Are Lower Than Category 2 and 3 Initial Scenario Probabilities

If π'_w and π''_i are greater than the probability of category 2 and 3 scenarios, it means that the impact of the difference between the weather and incident event durations Δ_{wi} is larger than the impact of the expected demand-plus-weather, or demand-plus-incident initial scenarios. In this case, the shorter event must be modeled with a longer duration in Step 3 and the procedure needs to be restarted from Step 3. Before proceeding to Step 7, Equation 37-24 and Equation 37-25 must hold for all category 2 and 3 scenarios:

$$\pi''_i < P_{wi}, w = 0$$

Equation 37-24

$$\pi'_w < P_{wi}, i = 0$$

Equation 37-25

Step 7: Calculate Remaining Probabilities of Category 2 and 3 Scenarios

This step calculates the remaining initial scenario probabilities for category 2 and 3 study period scenarios. These probabilities represent the portion of initial scenario probabilities not modeled as part of category 4 study period scenarios. Equation 37-26 provides the remaining probability for category 2 scenarios p_{w0} , while Equation 37-27 provides the remaining probability for category 3 scenarios p_{0i} .

$$p_{w0} = P_{wi} - \pi'_w$$

Equation 37-26

$$p_{0i} = P_{wi} - \pi''_i$$

Equation 37-27

where all variables are as defined previously. The check of probabilities in Step 6 assures that the probabilities calculated here in Step 7 are positive.

Step 8: Adjust Category 2 and 3 Probabilities

The adjusted probability of a category 2 scenario π_{w0} is computed from Equation 37-28, using the remaining probability of a category 2 scenario determined in Step 7:

$$\pi_{w0} = p_{w0} \times \left(\frac{t_{SP}}{\text{Round}(\tau_w^{wea})} \right)$$

Equation 37-28

A similar process is used to calculate the adjusted probability of a category 3 scenario π_{0i} :

$$\pi_{0i} = p_{0i} \times \left(\frac{t_{SP}}{\text{Round}(\tau_i^{inc})} \right)$$

Equation 37-29

Step 9: Check Necessity of Modeling More Than One Event Per Study Period in Category 2 and 3 Scenarios

If the overall sum of probabilities for category 2–4 scenarios is greater than the sum of the initial scenario probabilities, some category 2 and 3 scenarios will need to have more than one event to have their probabilities match the initial scenario probabilities. This is because all the probabilities are time-based, and by increasing the duration, the probability can be reduced, as can be shown from Equation 37-28 and Equation 37-29.

Step 10: Calculate Category 1 Scenario Probability

The difference between the sum of probabilities of the initial scenarios, and the current sum of probabilities for category 2–4 study period scenarios is assigned to the category 1 (normal condition) scenario.

OPERATIONAL SCENARIO GENERATION

Incident impacts on freeway facilities are sensitive to the facility geometry (e.g., number of lanes, segment type, and segment length) and the prevailing demand level. The effect of an incident on travel time could vary with demand, with higher impacts anticipated when the facility is operating near capacity. Therefore, to capture the real effect of an incident on the freeway facility, an incident's location, start time, and duration are allowed to vary. The method assumes two possible incident start times (start and middle of the study period), three possible durations (25th, 50th, and 75th percentile), and three possible locations (first, middle, or last basic segment) on the facility.

Weather events are assumed to affect the entire facility at once, but their start times are allowed to vary. The method assumes two possible start times (start and middle of the study period) for a weather event and one event duration (the average).

Operational scenarios must be developed for each study period scenario, incorporating all of the combinations start time, duration, and location applicable to a particular event type (weather or incident).

Operational Scenario Probabilities

The view of the system operator is taken in developing the travel time distribution. That is, the operator is interested in the aggregate performance of the facility over each 15-min analysis period during the reliability reporting period.

For the category 1 (normal condition) scenario with an adjusted probability of π_{00} and a total number of analysis periods within the study period A , the facility travel time in each 15-min analysis period will be given a probability equal to π_{00} / A . For example, if the study period is 6 h long (24 analysis periods) and the adjusted category 1 probability is 0.0084%, each analysis period will be given a probability of $0.0084\% / 24 = 0.00035\%$.

For a category 2 (demand-plus-weather) scenario with an adjusted probability of π_{w0} , the facility travel time for each analysis period will be given a probability equal to $\pi_{w0} / (2 \times A)$. The reason for the division by 2 is that two operational scenarios will be generated, once with the weather event at the start of the study period and once at the middle of the study period.

For a category 3 (demand-plus-incident) scenario with an adjusted probability of π_{oi} , the facility travel time for each analysis period will be given a probability equal to $\pi_{oi} / (2 \times 3 \times 3 \times A)$. Here, 18 operational scenarios will be generated, one for each combination of three locations, three durations, and two start times.

Finally, for a category 4 (demand, weather, and incident) scenario with an adjusted probability of π_{wi} , the facility travel time for each analysis period will be

given a probability equal to $\pi_{wi} / (2 \times 3 \times 3 \times A)$. A total of 18 operational scenarios will be generated, one for each combination of three incident locations, three incident durations, and two incident start times. Since severe weather starts at the same time as the incident, there is no need for an additional division by 2.

Post-processing Operational Scenarios

It is possible that some operational scenarios are infeasible, because a facility may not have the same number of cross-sectional lanes throughout. For example, in the process of varying the incident location, a scenario could result in a total segment closure, such as modeling a two-lane closure on a two-lane segment. These infeasible scenarios are purged from the final list of operational scenarios, and their probabilities are re-assigned proportionally to the remaining operational scenarios based on their probability of occurrence.

Estimating the Maximum Number of Scenarios

Equation 37-30 can be used to estimate the number of operational scenarios that will be generated. Due to the merging of some demand patterns and the application of minimum thresholds for including a scenario, it is possible to have some weather and incident events with a zero probability. The total number of scenarios as a function of different impacting factors is:

$$N = N_{\text{Demand}} + [N_{\text{Demand}} \times (N_{\text{Weather}} - 1)] \times C_{\text{Weather}} + [N_{\text{Demand}} \times (N_{\text{Incidents}} - 1)] \times C_{\text{Incidents}} + [N_{\text{Demand}} \times (N_{\text{Weather}} - 1) \times (N_{\text{Incidents}} - 1)] \times C_{\text{Incidents}} \times C_{\text{Weather}}$$

Equation 37-30

N denotes the total number of scenarios, while N_{Weather} and $N_{\text{Incidents}}$ are the weather categories (11) and incident categories (6) aggregated across demand patterns. Each incident category produces 18 operational scenarios ($C_{\text{Incidents}}$), while each weather scenario produces 2 operational scenarios (C_{Weather}). If the 12 default demand patterns are used, Equation 37-30 determines that a maximum of 22,932 operational scenarios will be generated. The actual number of operational scenarios generated could be up to an order of magnitude less.

MIGRATING SCENARIOS TO THE CHAPTER 10 METHOD

At this point, all of the operational scenarios have been specified. Next, each scenario specification is used to generate input data for the Chapter 10 freeway facilities procedure. The three basic types of information required are geometry, capacity, and demand data.

Geometric Information

The following is the necessary geometric information that is required for base conditions for the freeway facility:

- Segment types (basic, weave, merge, diverge);
- Segment lengths;
- Number of lanes for each segment; and
- Free-flow speed (mainline and ramps).

Two of these items can be altered in a given operational scenario: number of operational lanes and free-flow speed, depending on the type of weather and/or incident event that occurs in the scenario.

Demand Adjustments

Demand in Data Poor Environments

When agencies have no access to detailed demand information for the freeway facility, daily demands are computed based on AADT estimates for the facility, combined with day-of-week and month-of-year demand ratios. Since each operational scenario is associated with an initial scenario, and each initial scenario is a combination of a demand pattern, weather event, and incident event, the initial scenario's demand pattern, multiplied by the appropriate demand ratio, is used to generate the demand for a given operational scenario.

Hourly variations supplied by the analyst are used to generate hourly demands from the daily demand in a given operational scenario. Linear interpolation is used to estimate 15-min analysis period demands as shown in Equation 37-31.

Equation 37-31

$$(D_s^t)_k = (4 \times K_t^{15min}) \times (DR_k) \times \left(\frac{DAADT_s}{24} \right)$$

where

$(D_s^t)_k$ = hourly demand in segment s and analysis period t for operational scenario k (veh/h),

K_t^{15min} = portion of demand in analysis period t ,

DR_k = aggregated demand ratio for operational scenario k , and

$DAADT_s$ = directional AADT in segment s (veh).

The aggregation used for DR_k is based on the number of days that the demand pattern is in effect.

Demand in Data-Rich Environments

In a data-rich environment, hourly demand values for all analysis periods of a study period are provided through a detailed seed file. The only adjustment required is to include a daily demand multiplier for the seed study period DM_{Seed} . Then, the hourly demand $(D_s^t)_k$ on segment s in time period t for operational scenario k is:

Equation 37-32

$$(D_s^t)_k = \left(\frac{(D_s^t)_{Seed}}{DM_{Seed}} \right) (DR_k)$$

where all variables are as defined previously.

Capacity and Speed Adjustments

General Process

Modeling an incident or weather event on a freeway facility is done by (a) applying a Capacity Adjustment Factor (CAF), (b) applying a Speed Adjustment Factor (SAF) and, in the case of a lane closure, (c) setting the number of operating lanes for the segment with the lane closure.

The scenario generator distinguishes between the capacity loss due to closed lanes and the frictional effect on the remaining open lanes. The former type of loss is specified through the number of operating lanes, while the latter type of loss is specified by the CAF for the incident or work zone.

Reductions in free-flow speed due to weather events are specified by the SAF associated with the weather event. There is no evidence in the literature that incidents affect the prevailing free-flow speed (δ); therefore, a default value of 1.00 is used as the free-flow SAF for incidents.

The analyst may define local CAFs and SAFs for incident and weather events. Otherwise, the default values given in Exhibit 36-25 in Chapter 36, Travel Time Reliability, are used. When both weather and incident conditions are present, their respective CAFs and SAFs are multiplied together as follows:

$$CAF = CAF_i^{Inc} \times CAF_w^{Wea}$$

$$SAF = SAF_i^{Inc} \times SAF_w^{Wea}$$

Equation 37-33

Equation 37-34

where

CAF = capacity adjustment factor,

CAF_i^{Inc} = capacity adjustment factor for incident type i ,

CAF_w^{Wea} = capacity adjustment factor for weather type w ,

SAF = speed adjustment factor,

SAF_i^{Inc} = speed adjustment factor for incident type i , and

SAF_w^{Wea} = speed adjustment factor for weather type w .

These combined CAFs and SAFs are calculated for each segment and each analysis period.

Basic Freeway Segments

A modified version of Equation 25-1 from Chapter 25, Freeway Facilities: Supplemental, is used in combination with the combined CAFs and SAFs to predict basic freeway segment performance under incident and severe weather scenarios:

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

Equation 37-35

where

S = segment speed (mi/h),

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

SAF = segment speed adjustment factor,

C = original segment capacity (pc/h/ln),
 CAF = capacity adjustment factor, and
 v_p = segment flow rate (pc/h/ln).

Merge, Diverge, and Weaving Segments

Equation 37-35 is ultimately intended for application to basic freeway segments. However, in both the HCM2000 and in HCM 2010, it is also applied to the analysis of merge/diverge and weaving segments with a CAF less than 1.0. The remainder of this section describes the adaptation of CAF and SAF to these other HCM freeway segment types.

A challenge arises in both the merge/diverge and weaving methods when considering CAF and SAF, as these methods do not use segment capacity as an input in the speed prediction equation. In essence, these methods violate the fundamental equation of traffic flow (speed = flow \times density). Instead, both methods first estimate segment capacity and then perform a check to assure that traffic demands are below that capacity (otherwise, the demand-to-capacity ratio is greater than 1 and the oversaturated module is invoked). If the segment passes the capacity check, the segment speed is estimated from an independent regression equation.

CAFs for Merge, Diverge, and Weaving Segments

For reliability analysis, the base capacity is adjusted with the appropriate CAF before performing the demand-to-capacity check as follows:

Equation 37-36

$$\text{Adjusted Capacity} = \text{Base Capacity} \times \text{CAF}$$

where *Adjusted Capacity* is the capacity used to perform the demand-to-capacity check, *Base Capacity* is the merge/diverge or weaving segment capacity estimated from Chapter 12 or 13, respectively, and CAF is the capacity adjustment factor. SAF is subsequently applied as a multiplier of FFS in the speed prediction equation, as discussed below for merge/diverge and weaving segments. The application of CAF and SAF is generally consistent with the basic segment procedure, but with the caveat that the factors are applied in two (or more) separate steps.

SAFs for Merge and Diverge Segments

Exhibit 13-11 gives equations for estimating the average speed of vehicles within the on-ramp influence area and in the outer lanes of the freeway. These equations are updated as shown in Exhibit 37-21 to incorporate the SAF. Similarly, the equations in Exhibit 13-12 for off-ramp influence areas are updated as shown in Exhibit 37-22.

Average Speed in	Equation
Ramp influence area	$S_R = (FFS \times SAF) - ((FFS \times SAF) - 42)M_S$ $M_S = 0.321 + 0.0039e^{(v_{R12}/1,000)} - 0.002(L_A S_{FR} \times SAF / 1,000)$
Outer lanes of freeway	$S_O = FFS \times SAF \quad v_{OA} < 500 \text{ pc/h}$ $S_O = (FFS \times SAF) - 0.0036(v_{OA} - 500) \quad 500 \text{ pc/h} \leq v_{OA} \leq 2,300 \text{ pc/h}$ $S_O = (FFS \times SAF) - 6.53 - 0.006(v_{OA} - 2,300) \quad v_{OA} > 2,300 \text{ pc/h}$

Exhibit 37-21
Estimating Speed at On-Ramp (Merge) Junctions with SAF Consideration

Average Speed in	Equation
Ramp influence area	$S_R = (FFS \times SAF) - ((FFS \times SAF) - 42)D_S$ $D_S = 0.883 + 0.00009v_R - 0.013(S_{FR} \times SAF)$
Outer lanes of freeway	$S_O = 1.097(FFS \times SAF) \quad v_{OA} < 1,000 \text{ pc/h}$ $S_O = 1.097(FFS \times SAF) - 0.0039(v_{OA} - 1,000) \quad v_{OA} \geq 1,000 \text{ pc/h}$

Exhibit 37-22
Estimating Speed at Off-Ramp (Diverge) Junctions with SAF Consideration

The variables used in Exhibit 37-21 and Exhibit 37-22 are as follows:

S_R = average speed of vehicles within the ramp influence area (mi/h); for merge areas, this includes all ramp and freeway vehicles in Lanes 1 and 2; for diverge areas, this includes all vehicles in Lanes 1 and 2;

S_O = average speed of vehicles in outer lanes of the freeway, adjacent to the 1,500-ft ramp influence area (mi/h);

S = average speed of all vehicles in all lanes within the 1,500-ft length covered by the ramp influence area (mi/h);

FFS = free-flow speed of the freeway (mi/h);

SAF = speed adjustment factor for the ramp segment (decimal);

S_{FR} = free-flow speed of the ramp (mi/h);

L_A = length of acceleration lane (ft);

L_D = length of deceleration lane (ft);

v_R = demand flow rate on ramp (pc/h);

v_{12} = demand flow rate in Lanes 1 and 2 of the freeway immediately upstream of the ramp influence area (pc/h);

v_{R12} = total demand flow rate entering the on-ramp influence area, including v_{12} and v_R (pc/h);

v_{OA} = average demand flow per lane in outer lanes adjacent to the ramp influence area (not including flow in Lanes 1 and 2) (pc/h/ln);

M_S = speed index for on-ramps (merge areas); this is simply an intermediate computation that simplifies the equations; and

D_S = speed index for off-ramps (diverge areas); this is simply an intermediate computation that simplifies the equations.

SAFs for Weaving Segments

The equations for calculating the speed of weaving and nonweaving vehicles in weaving segments (Equations 12-18 through 12-20) are modified by multiplying each occurrence of FFS by SAF, and the space mean speed of all vehicles in the weaving segment (Equation 12-21) is now computed using the adjusted values of weaving and nonweaving vehicle speeds:

Equation 37-37
$$S_W = 15 + \left(\frac{(FFS \times SAF) - 15}{1 + W} \right)$$

Equation 37-38
$$W = 0.226 \left(\frac{LC_{ALL}}{L_S} \right)^{0.789}$$

Equation 37-39
$$S_{NW} = (FFS \times SAF) - (0.0072LC_{MIN}) - \left(0.0048 \frac{v}{N} \right)$$

Equation 37-40
$$S = \frac{v_W + v_{NW}}{\left(\frac{v_W}{S_W} \right) + \left(\frac{v_{NW}}{S_{NW}} \right)}$$

where

S_W = average speed of weaving vehicles within the weaving segment (mi/h);

S_{NW} = average speed of nonweaving vehicles within the weaving segment (mi/h);

FFS = free-flow speed of the weaving segment (mi/h);

SAF = speed adjustment factor for the weaving segment (decimal);

W = weaving intensity factor;

L_S = weaving segment length (ft);

LC_{ALL} = total lane-changing rate of all vehicles in the weaving segment, from Chapter 12 (lc/h);

LC_{MIN} = minimum rate of lane changing that must exist for *all* weaving vehicles to successfully complete their weaving maneuvers, from Chapter 12 (lc/h);

v = total demand flow rate in the weaving segment = $v_W + v_{NW}$ (pc/h);

N = number of lanes within the weaving section;

v_W = weaving demand flow rate in the weaving segment (pc/h); and

v_{NW} = nonweaving demand flow rate in the weaving segment (pc/h).

4. URBAN STREET SCENARIO GENERATION

WEATHER EVENT PREDICTION

The weather event procedure is used to predict weather events during the reliability reporting period. The events predicted include rainfall and snowfall. Also predicted is the time following each event that the pavement remains wet or covered by snow or ice. The presence of these conditions has been found to have an influence on running speed and intersection saturation flow rate.

The weather event procedure consists of a series of calculation steps. The calculations associated with each step are described in the following paragraphs. A random number is used in several of the steps. All random numbers have a real value that is uniformly distributed from 0.0 to 1.0.

Step 1: Precipitation Prediction

The probability of precipitation for any given day is computed using the following equation.

$$P(\text{precip})_m = \frac{Ndp_m}{Nd_m} \quad \text{Equation 37-41}$$

where

$P(\text{precip})_m$ = probability of precipitation in any given day of month m ,

Ndp_m = number of days with precipitation of 0.01 in. or more in month m (d),
and

Nd_m = total number of days in month m (d).

For each day considered, the following rule is checked to determine whether precipitation occurs:

$$\begin{aligned} &\text{No precipitation if } Rp_d \geq P(\text{precip})_d \\ &\text{Precipitation if } Rp_d < P(\text{precip})_d \end{aligned} \quad \text{Equation 37-42}$$

where

$P(\text{precip})_d$ = probability of precipitation for day d , and

Rp_d = random number for precipitation for day d .

Step 2: Precipitation Type

If precipitation occurs, then the following equation is used to estimate the average temperature during the weather event for the subject day.

$$T_{d,m} = \text{normal}^{-1}(p = Rg_d, \mu = \bar{T}_m, \sigma = s_T) \quad \text{Equation 37-43}$$

where

$T_{d,m}$ = average temperature for day d of month m (°F),

Rg_d = random number for temperature for day d ,

\bar{T}_m = normal daily mean temperature in month m (°F),

s_T = standard deviation of daily mean temperature in a month
(= 5.0) (°F), and

$normal^{-1}(p, \mu, \sigma)$ = value associated with probability p for a cumulative normal distribution with mean μ and standard deviation σ .

The average temperature for the day is used to determine whether the precipitation is in the form of rain or snow. The following rule is checked to determine whether the precipitation that day is in the form of rain or snow.

Equation 37-44

Rain if $T_{d,m} \geq 32^\circ\text{F}$

Snow if $T_{d,m} < 32^\circ\text{F}$

Step 3: Rain Intensity

The following equation is used to estimate the rainfall rate during a rain event.

Equation 37-45

$$rr_{d,m} = \text{gamma}^{-1}(p = Rr_d, \mu = \bar{r}r_m, \sigma = s_{rr,m})$$

where

$rr_{d,m}$ = rainfall rate for the rain event occurring on day d of month m
(in./h),

Rr_d = random number for rainfall rate for day d ,

$\bar{r}r_m$ = precipitation rate in month m (in./h),

$s_{rr,m}$ = standard deviation of precipitation rate in month m (= $1.0 \bar{r}r_m$)
(in./h), and

$\text{gamma}^{-1}(p, \mu, \sigma)$ = value associated with probability p for a cumulative gamma distribution with mean μ and standard deviation σ .

The average precipitation rate (and its standard deviation) is based on time periods when precipitation is falling. Thus, the average precipitation rate represents an average for all hours for which precipitation is falling (and excluding any hours when precipitation is not falling).

The following equation is used to estimate the total amount of rainfall for a rain event. It is assumed here that there is one rain event for each day with precipitation.

Equation 37-46

$$tr_{d,m} = \text{gamma}^{-1}(p = Rt_d, \mu = \bar{t}r_m, \sigma = s_{tr,m})$$

with

Equation 37-47

$$\bar{t}r_m = \frac{tp_m}{Ndp_m}$$

Equation 37-48

$$s_{tr,m} = \text{Min}(2.5\bar{t}r_m, 0.65)$$

where

$tr_{d,m}$ = total rainfall for the rain event occurring on day d of month m (in./event),

Rt_d = random number for rainfall total for day d ($= Rr_d$),

\bar{tr}_m = average total rainfall per event in month m (in./event),

$s_{tr,m}$ = standard deviation of total rainfall in month m (in./event),

tp_m = total normal precipitation for month m (in.), and

Ndp_m = number of days with precipitation of 0.01 in. or more in month m (d).

Total rainfall for a rain event represents the product of rainfall rate and rain event duration. Thus, the total rainfall amount is highly correlated with the rainfall rate. For reliability evaluation, total rainfall is assumed to be perfectly correlated with rainfall rate such that they share the same random number. This approach may result in slightly less variability in the estimated total rainfall; however, it precludes the occasional calculation of unrealistically long or short rain events.

Step 4: Rainfall Duration

The following equation is used to estimate the rainfall duration for a rain event:

$$dr_{d,m} = \frac{tr_{d,m}}{rr_{d,m}}$$

Equation 37-49

where

$dr_{d,m}$ = rainfall duration for the rain event occurring on day d of month m (h/event),

$tr_{d,m}$ = total rainfall for the rain event occurring on day d of month m (in./event), and

$rr_{d,m}$ = rainfall rate for the rain event occurring on day d of month m (in./h).

The duration computed with Equation 37-49 is used in a subsequent step to determine whether an analysis period is associated with a rain event. To simplify the analytics in this subsequent step, it is assumed that no rain event extends beyond midnight. To ensure this outcome, the duration computed from Equation 37-49 is compared with the time duration between the start of the study period and midnight. The rainfall duration is then set to equal the smaller of these two values.

Step 5: Start Time of Weather Event

The hour of the day that the rain event starts is determined randomly. The start hour is computed using the following equation.

$$ts_{d,m} = (24 - dr_{d,m}) R_{s,d}$$

Equation 37-50

where

$ts_{d,m}$ = start of rain event on day d of month m (h),

24 = number of hours in a day (h/day),

$dr_{d,m}$ = rainfall duration for the rain event occurring on day d of month m (h/event), and

$R_{s,d}$ = random number for rain event start time for day d .

The start time from Equation 37-50 is rounded to the nearest hour for 1-h analysis periods, or to the nearest quarter hour for 15-min analysis periods.

Step 6: Wet Pavement Duration

Following a rain event, the pavement typically remains wet for some length of time. The presence of wet pavement can influence road safety by reducing surface-tire friction. Research (9) indicates that wet pavement time can be computed using the following equation.

Equation 37-51

$$dw_{d,m} = dr_{d,m} + do_{d,m} + dd_{d,m}$$

with

Equation 37-52

$$dd_{d,m} = 0.888 \exp(-0.0070 T_{d,m}) + 0.19 I_{\text{night}}$$

where

$dw_{d,m}$ = duration of wet pavement for rain event occurring on day d of month m (h/event),

$dr_{d,m}$ = rainfall duration for the rain event occurring on day d of month m (h/event), and

$do_{d,m}$ = duration of pavement runoff for rain event occurring on day d of month m (= 0.083) (h/event),

$T_{d,m}$ = average temperature for day d of month m (°F),

I_{night} = indicator variable for day/night (= 0.0 if rain starts between 6:00 a.m. and 6:00 p.m., 1.0 otherwise), and

$dd_{d,m}$ = duration of drying time for rain event occurring on day d of month m (h/event).

The duration computed with Equation 37-51 is used in a subsequent step to determine whether an analysis period is associated with wet pavement conditions. To simplify the analytics in this subsequent step, it is assumed that no rain event extends beyond midnight. To ensure this outcome, the duration computed from Equation 37-51 is compared with the time duration between the start of the rain event and midnight. The wet pavement duration is then set to equal the smaller of these two values.

Step 7: Snow Intensity and Duration

The snowfall rate (i.e., intensity) and duration are computed using the calculation sequence in Steps 3 to 6. The equations are the same. The average snowfall rate and average snow total per event are computed by multiplying the

average precipitation rate and average total rainfall per event, respectively, by the ratio of snow depth to rain depth. This ratio is estimated at 10 in./in. based on an analysis of weather data reported by the National Climatic Data Center (NCDC, 10).

In Step 6, the duration of pavement runoff is defined differently when applied to snow events. Specifically, it is defined as the time after the snow stops falling that snow pack (or ice) covers the pavement. After this time period elapses, the pavement is exposed and drying begins. A default value for this variable is provided in Section 5, Applications, in Chapter 36.

Step 8: Identify Analysis Period Weather

Steps 1 through 7 are repeated for each day of a two-year period, starting with the first day of the reliability reporting period. This two-year record of weather events is used in the traffic incident procedure to estimate the weather-related incident frequency.

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. If the pavement is wet during an analysis period, then the precipitation type (i.e., rain or snow) is recorded for that period. If precipitation is falling, then the precipitation rate is also recorded.

The duration of precipitation and wet pavement from Equation 37-49 and Equation 37-51, respectively, are rounded to the nearest hour for 1-h analysis periods, or to the nearest quarter hour for 15-min analysis periods. This rounding is performed to ensure the most representative match between event duration and analysis period start/end times.

TRAFFIC DEMAND VARIATION PREDICTION

The traffic demand variation procedure is used to identify the appropriate traffic demand adjustment factors for each analysis period in the reliability reporting period. One set of factors account for systematic volume variation by hour of day, day of week, and month of year. Default values for these factors are provided in Section 5, Applications, in Chapter 36.

A random variation adjustment factor is also available and can be included, if desired, by the analyst. It accounts for the random variation in volume that occurs among 15-min time periods. This factor is described in more detail in the Scenario Dataset Generation Procedure section.

The procedure includes two adjustment factors to account for a reduction in traffic demand during inclement weather. One factor addresses the demand change when it is raining. The second factor addresses demand change when it is snowing. Default values for these factors are provided in Section 5, Applications, in Chapter 36.

This procedure does not address traffic diversion due to the presence of work zones or special events. Their accommodation in a reliability evaluation is discussed in Analysis Techniques subsection of Section 4, Urban Street Methodology, in Chapter 36.

If the traffic volumes provided in the base dataset and the alternative datasets are computed using planning procedures, then the volumes in the dataset are based on the average day of week and month of year. In this situation, the adjustment factors for day of week and month of year are set to a value of 1.0.

The factors identified in this procedure are subsequently used in the scenario dataset generation procedure to compute the demand volume for the subject urban street facility.

TRAFFIC INCIDENT PREDICTION

The traffic incident procedure is used to predict incident date, time, and duration. It also determines incident event type (i.e., crash or non-crash), severity level, and location on the facility. Location is defined by the specific intersection or segment on which the incident occurs and whether the incident occurs on the shoulder, one lane, or multiple lanes. The procedure uses weather event and traffic demand variation information from the previous procedures in the incident prediction process.

The traffic incident procedure consists of a set of calculation steps. The calculations associated with each step are described in the following paragraphs. A random number is used in several of the steps. All random numbers have a real value that is uniformly distributed from 0.0 to 1.0.

Step 1: Compute the Equivalent Crash Frequency for Weather

Crash frequency increases when the road is wet, covered by snow, or covered by ice. The effect of weather on crash frequency is incorporated in the reliability methodology by converting the input crash frequency data into an equivalent crash frequency for each type of weather condition. The equivalent crash frequency for dry pavement conditions is defined using the following equation:

Equation 37-53

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

where

$F_{c_{str(i),dry}}$ = equivalent crash frequency when every day is dry for street location i of type str ($str = int$: intersection, seg : segment) (crashes/yr),

$F_{c_{str(i)}}$ = expected crash frequency for street location i of type str (crashes/yr),

8,760 = number of hours in a year (h/yr),

Ny = total number of years (yr),

Nh_{dry} = total number of hours in Ny years with dry conditions (h),

Nh_{rf} = total number of hours in Ny years with rainfall conditions (h),

Nh_{wp} = total number of hours in Ny years with wet pavement and not raining (h),

Nh_{sf} = total number of hours in Ny years with snowfall conditions (h),

Nh_{sp} = total number of hours in Ny years with snow or ice on pavement and not snowing (h),

$CFAF_{rf}$ = crash frequency adjustment factor for rainfall,

$CFAF_{wp}$ = crash frequency adjustment factor for wet pavement (not raining),

$CFAF_{sf}$ = crash frequency adjustment factor for snowfall, and

$CFAF_{sp}$ = crash frequency adjustment factor for snow or ice on pavement (not snowing).

The equivalent crash frequency for non-dry conditions is computed using the following equation. The crash frequency adjustment factor (CFAF) for dry weather $CFAF_{str(i),dry}$ is 1.0.

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

Equation 37-54

where

$Fc_{str(i),wea}$ = equivalent crash frequency when every day has weather condition *wea* (*wea* = *dry*: no precipitation and dry pavement, *rf*: rainfall, *wp*: wet pavement but not raining, *sf*: snowfall, *sp*: snow or ice on pavement but not snowing) for street location *i* of type *str* (crashes/yr);

$Fc_{str(i),dry}$ = equivalent crash frequency when every day is dry for street location *i* of type *str* (crashes/yr); and

$CFAF_{wea}$ = crash frequency adjustment factor for weather condition *wea*.

Equation 37-53 requires the total number of hours for each weather condition in the vicinity of the subject facility. A weather history that extends for two or more years should be used to reduce the random variability in the data. These hours can be obtained from available weather records, or estimated using the weather event procedure.

This step is separately applied to each intersection and segment on the facility. When applied to intersections, the expected crash frequency Fc is provided by the analyst for the subject intersection. When applied to segments, the expected crash frequency is provided by the analyst for subject segment.

The CFAF represents the ratio of hourly crash frequency during the weather event divided by the hourly crash rate during clear, dry hours. It is computed using one or more years of historic weather data and crash data for the region in which the subject facility is located. Default values for these factors are provided in Section 5, Applications, in Chapter 36.

Step 2: Establish the CFAFs for Work Zones and Special Events

If the analysis period occurs during a work zone or special event, then the CFAF variable for segments $CFAF_{str}$ and the CFAF variable for intersections $CFAF_{int}$ are set equal to the values provided by the analyst. Otherwise, $CFAF_{str}$ and $CFAF_{int}$ equal 1.0. This step is repeated for each analysis period of the reliability reporting period.

Step 3: Determine Whether an Incident Occurs

During this step, each of the 24 hours in the subject day is examined to determine if an incident occurs. The analysis separately considers each street location (i.e., intersection and segment). At each street location, each of the following 12 incident types is separately addressed. Each of these types is separately considered for each hour of the day (whether the hour coincides with an analysis period is determined in a subsequent step).

- Crash, one lane blocked, fatal or injury.
- Crash, two or more lanes blocked, fatal or injury.
- Crash, shoulder location, fatal or injury.
- Crash, one lane blocked, property damage only.
- Crash, two or more lanes blocked, property damage only.
- Crash, shoulder location, property damage only.
- Non-crash, one lane blocked, breakdown.
- Non-crash, two or more lanes blocked, breakdown.
- Non-crash, shoulder location, breakdown.
- Non-crash, one lane blocked, other.
- Non-crash, two or more lanes blocked, other.
- Non-crash, shoulder location, other.

“Other” refers to any kind of non-breakdown incident (e.g., spill, dropped load).

Initially, the weather event data are checked to determine whether the subject day and hour are associated with rainfall, wet pavement and not raining, snowfall, or snow or ice on pavement and not snowing. For a given day, street location, and hour of day, the average incident frequency is computed using the following equation based on the weather present at that hour and day.

Equation 37-55

$$F_{i_{str(i),wea(h,d)}} = CFAF_{str} \frac{F_{C_{str(i),wea}}}{p_{C_{str,wea}}}$$

where

$F_{i_{str(i),wea(h,d)}}$ = expected incident frequency for street location i of type str and weather condition $wea(h,d)$ during hour h and day d (incidents/yr);

$CFAF_{str}$ = crash frequency adjustment factor for street location type str ;

$F_{C_{str(i),wea}}$ = equivalent crash frequency when every day has weather condition wea for street location i of type str (crashes/yr); and

$p_{C_{str,wea}}$ = proportion of incidents that are crashes for street location type str and weather condition wea .

Default values for the proportion of incidents are provided in Section 5, Applications, in Chapter 36.

The incident frequency is converted to an hourly frequency that is sensitive to traffic demand variation by hour of day, day of week, and month of year. The converted frequency is computed using the following equation.

$$f_{i_{str(i),wea(h,d),h,d}} = \frac{F_{i_{str(i),wea(h,d)}}}{8,760} (24 f_{hod,h,d}) f_{dow,d} f_{moy,d}$$

Equation 37-56

where

$f_{i_{str(i),wea(h,d),h,d}}$ = expected hourly incident frequency for street location i of type str and weather condition $wea(h,d)$ during hour h and day d (incidents/h),

$F_{i_{str(i),wea(h,d)}}$ = expected incident frequency for street location i of type str and weather condition $wea(h,d)$ during hour h and day d (incidents/yr),

8,760 = number of hours in a year (h/yr),

24 = number of hours in a day (h/day),

$f_{hod,h,d}$ = hour-of-day adjustment factor based on hour h and day d ,

$f_{dow,d}$ = day-of-week adjustment factor based on day d , and

$f_{moy,d}$ = month-of-year adjustment factor based on day d .

The hour-of-day adjustment factor includes a day subscript because its values vary depending on whether the day occurs during a weekday or weekend. The day subscript for the day-of-week factor is used to determine which of the seven weekdays is associated with the subject day. Similarly, the month subscript is used to determine which of the twelve months is associated with the subject day for the month-of-year factor. Default values for these adjustment factors are provided in Section 5, Applications, in Chapter 36.

Incidents for a given day, street location, incident type, and hour of day are assumed to follow a Poisson distribution. For any given combination of conditions, the probability of more than one incident of a given type is negligible, which simplifies the math such that the question of whether an incident occurs is reduced to whether there are zero incidents or one incident of a given type. Equation 37-57 is used to compute the probability of no incidents occurring. Default values for the proportion of incidents are provided in Section 5, Applications, in Chapter 36.

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

Equation 37-57

where

$p0_{str(i),wea(h,d),con,lan,sev,h,d}$ = probability of no incident for street location i of type str , weather condition $wea(h,d)$ during hour h and day d , event type con ($con = cr$: crash, nc : non-crash), lane location lan ($lan = 1L$: one lane, $2L$ two or more lanes, sh : shoulder), and severity sev ($sev = pdo$: property damage only, fi : fatal or injury, bkd : breakdown, oth : other);

$f_{i_{str(i),wea(h,d),h,d}}$ = expected hourly incident frequency for street location i of type str and weather condition $wea(h,d)$ during hour h and day d (incidents/h); and

$p_{i_{str,wea(h,d),con,lan,sev}}$ = proportion of incidents for street location type str ,

weather condition $wea(h,d)$ during hour h and day d ,
event type con , lane location lan , and severity sev .

The following rule is checked to determine whether the incident of a specific type occurs.

Equation 37-58

$$\text{No incident if } Ri_{str(i),wea(h,d),con,lan,sev,h,d} \leq p0_{str(i),wea(h,d),con,lan,sev,h,d}$$

$$\text{Incident if } Ri_{str(i),wea(h,d),con,lan,sev,h,d} > p0_{str(i),wea(h,d),con,lan,sev,h,d}$$

where

$Ri_{str(i),wea(h,d),con,lan,sev,h,d}$ = random number for incident for street location i of type str , weather condition $wea(h,d)$ during hour h and day d , event type con , lane location lan , and severity sev ; and

$p0_{str(i),wea(h,d),con,lan,sev,h,d}$ = probability of no incident for street location i of type str , weather condition $wea(h,d)$ during hour h and day d , event type con ($con = cr$: crash, nc : non-crash), lane location lan , and severity sev .

Step 4: Determine Incident Duration

If the result of Step 3 indicates that an incident occurs for a given day, street location, incident type, and hour of day, then the calculations in this step are used to determine the incident duration. Each hour of the day is separately considered in this step.

Incident duration includes the incident detection time, response time, and clearance time. Research indicates that these values can vary by weather condition, event type, lane location, and severity. Default values for average incident duration are provided in Section 5, Applications, in Chapter 36.

The following equation is used to estimate the incident duration for a given incident:

Equation 37-59

$$di_{str(i),wea(h,d),con,lan,sev,h,d} = \text{gamma}^{-1}(p = Rd_{str(i),con,lan,sev,h,d}, \\ \mu = \bar{di}_{str,wea(h,d),con,lan,sev}, \\ \sigma = S_{str,wea(h,d),con,lan,sev})$$

where

$di_{str(i),wea(h,d),con,lan,sev,h,d}$ = incident duration for street location i of type str , weather condition $wea(h,d)$ during hour h and day d , event type con , lane location lan , and severity sev (h);

$Rd_{str(i),con,lan,sev,h,d}$ = random number for incident duration for street location i of type str for hour h and day d , event type con , lane location lan , and severity sev ;

$\bar{di}_{str(i),wea(h,d),con,lan,sev}$ = average incident duration for street location type str , weather condition $wea(h,d)$ during hour h and day d , event type con , lane location lan , and severity sev (h);

$S_{str,wea(h,d),con,lan,sev}$ = standard deviation of incident duration for street location type str , weather condition $wea(h,d)$ during hour

h and day d , event type con , lane location lan , and severity sev ($= 0.8 \bar{d}i_{str(i),wea(h,d),con,lan,sev}$) (h); and
 $gamma^{-1}(p,\mu,\sigma)$ = value associated with probability p for cumulative gamma distribution with mean μ and standard deviation σ).

The duration computed with Equation 37-59 is used in a subsequent step to determine whether an analysis period is associated with an incident. To simplify the analytics in this subsequent step, it is assumed that no incident extends beyond midnight. To ensure this outcome, the duration computed from Equation 37-59 is compared with the time duration between the start of the study period and midnight. The incident duration is then set to equal the smaller of these two values.

Step 5: Determine Incident Location

If the result of Step 3 indicates that an incident occurs for a given day, street location, incident type, and hour of day, then the calculations in this step are used to determine the incident location. For intersections, the location is determined to be one of the intersection legs. For segments, the location is determined to be one of the two travel directions. The location algorithm is volume-based so that the correct location determinations are made when addressing three-leg intersections or one-way streets. Each hour of the day is separately considered in this step.

Intersection Location

When a specific intersection is associated with an incident, the location of the incident is based on consideration of each intersection leg volume lv . This volume represents the sum of all movements entering the intersection on the approach lanes plus those movements exiting the intersection on the adjacent departure lanes. In the field, this volume would be measured by establishing a reference line from outside curb to outside curb on the subject leg (near the crosswalk) and counting all vehicles that cross the line, regardless of travel direction.

The leg volumes are then summed, starting with the leg associated with NEMA phase 2, to produce a cumulative volume by leg. These volumes are then converted to a proportion by dividing by the sum of the leg volumes. The calculation of these proportions is described by the following equations. One set of proportions is determined for the base dataset and for each work zone and special event dataset.

$$\begin{aligned}
 pv_{int(i),2} &= lv_{int(i),2} / (2 tv_{int(i)}) \\
 pv_{int(i),4} &= pv_{int(i),2} + lv_{int(i),4} / (2 tv_{int(i)}) \\
 pv_{int(i),6} &= pv_{int(i),4} + lv_{int(i),6} / (2 tv_{int(i)}) \\
 pv_{int(i),8} &= 1.0
 \end{aligned}$$

Equation 37-60

Equation 37-61

with

$$tv_{int(i)} = \sum_{j=1}^{12} v_{input, int(i), j}$$

where

$pv_{int(i), n}$ = cumulative sum of volume proportions for leg associated with NEMA phase n ($n = 2, 4, 6, 8$) at intersection i ,

$lv_{int(i), n}$ = leg volume (two-way total) for leg associated with NEMA phase n at intersection i (veh/h),

$tv_{int(i)}$ = total volume entering intersection i (veh/h), and

$v_{input, int(i), j}$ = movement j volume at intersection i (from dataset) (veh/h).

The leg location of the incident is determined by comparing a random number with the cumulative volume proportions. Using this technique, the likelihood of an incident being assigned to a leg is proportional to its volume, relative to the other leg volumes. The location is determined for a given intersection i by the following rule.

Equation 37-62

Incident on Phase 2 if $Rv_{int(i), con, lan, sev} \leq pv_{int(i), 2}$

Incident on Phase 4 if $pv_{int(i), 2} < Rv_{int(i), con, lan, sev} \leq pv_{int(i), 4}$

Incident on Phase 6 if $pv_{int(i), 4} < Rv_{int(i), con, lan, sev} \leq pv_{int(i), 6}$

Incident on Phase 8 if $pv_{int(i), 6} < Rv_{int(i), con, lan, sev} \leq pv_{int(i), 8}$

where

$Rv_{int(i), con, lan, sev}$ = random number for leg volume for intersection i , event type con , lane location lan , and severity sev ; and

$pv_{int(i), n}$ = cumulative sum of volume proportions for leg associated with NEMA phase n ($n = 2, 4, 6, 8$) at intersection i .

Segment Location

When a specific segment is associated with an incident, the location of the incident is based on consideration of the volume in each direction of travel dv . This volume is computed using the movement volume at the boundary intersection that uses NEMA phase 2 to serve exiting through vehicles. The volume in the phase 2 direction is computed as the sum of the movements exiting the segment at the boundary intersection (i.e., equals the approach lane volume). The volume in the phase 6 direction is computed as the sum of the movements entering the segment at the boundary intersection (i.e., it equals the departure lane volume). The two directional volumes are referenced to NEMA phases 2 and 6. The sum of these two volumes equals the phase 2 leg volume described in the previous subsection.

A cumulative volume proportion by direction is used to determine incident location. The calculation of these proportions is described by the following equations. One set of proportions is determined for the base dataset and for each work zone and special event dataset.

$$pv_{seg(i),2} = dv_{seg(i),2} / (dv_{seg(i),2} + dv_{seg(i),6})$$

$$pv_{seg(i),6} = 1.0$$

Equation 37-63

where

$pv_{seg(i),n}$ = volume proportion for the direction of travel served by NEMA phase n ($n = 2, 6$) on segment i ; and

$dv_{seg(i),n}$ = directional volume for the direction of travel served by NEMA phase n on segment i (veh/h).

The segment location of the incident is determined by comparing a random number with the cumulative volume proportions. Using this technique, the likelihood of an incident being assigned to a direction of travel is proportional to its volume, relative to the volume in the other direction. The location is determined for a given segment i by the following rule.

Incident in Phase 2 direction if $Rv_{seg(i),con,lan,sev} \leq pv_{seg(i),2}$

Incident in Phase 6 direction if $pv_{seg(i),2} < Rv_{seg(i),con,lan,sev} \leq pv_{seg(i),6}$

Equation 37-64

where

$Rv_{seg(i),con,lan,sev}$ = random number for volume for segment i , event type con , lane location lan , and severity sev ; and

$pv_{seg(i),n}$ = volume proportion for the direction of travel served by NEMA phase n ($n = 2, 6$) on segment i .

Step 6: Identify Analysis Period Incidents

Steps 3 through 5 are repeated for each hour of the subject day. As implied by the discussion to this point, all incidents are assumed to occur at the start of a given hour.

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, then its event type, lane location, severity, and street location are identified and recorded. Each subsequent analysis period coincident with the incident is also recorded.

The incident duration from Equation 37-59 is rounded to the nearest hour for 1-h analysis periods, or to the nearest quarter hour for 15-min analysis periods. This rounding is performed to ensure the most representative match between event duration and analysis period start/end times.

SCENARIO DATASET GENERATION

The scenario dataset generation procedure uses the results from the preceding three procedures to develop one HCM dataset for each analysis period in the reliability reporting period. As discussed previously, each analysis period is considered to be one scenario.

This procedure creates a new dataset for each analysis period. The HCM dataset is modified to reflect conditions present during a given analysis period. Modifications are made to the traffic volumes at each intersection and driveway.

They are also made to the saturation flow rate at intersections influenced by an incident or a weather event. The speed is also adjusted for segments influenced by an incident or a weather event.

The incident history developed by the traffic incident procedure is consulted during this procedure to determine if an incident occurs at an intersection or on a segment. If an incident occurs at an intersection, then the incident lane location data are consulted to determine which approach and movements are affected. If the incident occurs on the shoulder, then it is assumed that the shoulder in question is the outside shoulder (as opposed to the inside shoulder). If a one-lane incident occurs, then it is assumed that the incident occurs in the outside lane. If a two-or-more-lane incident occurs, then it is assumed that the incident occurs in the outside two lanes. It is also assumed that the incident occurs on the intersection approach lanes, as opposed to the departure lanes. This assumption is consistent with typical intersection crash patterns.

The scenario dataset generation procedure consists of a set of calculation steps. The calculations associated with each step are described in the following paragraphs.

Step 1: Acquire the Appropriate Dataset

During this step, the appropriate HCM dataset is acquired. This step proceeds day-by-day and analysis-period-by-analysis-period in chronologic order. The date is used to determine whether a work zone or special event is present. If one is present, then the appropriate alternative dataset is acquired. Otherwise, the base dataset is acquired. The hour-of-day, day-of-week, and month-of-year demand adjustment factors associated with each dataset are also acquired (as identified previously in the traffic demand variation procedure).

Step 2: Compute Weather Adjustment Factors

Signalized Intersections

The following equation is used to compute the saturation flow rate adjustment factor for analysis periods with poor weather conditions. It is used in Step 5 to estimate intersection saturation flow rate during weather events.

Equation 37-65

$$f_{rs,ap,d} = \frac{1.0}{1.0 + 0.48 R_{r,ap,d} + 0.39 R_{s,ap,d}}$$

where

$f_{rs,ap,d}$ = saturation flow adjustment factor for rainfall or snowfall during analysis period ap and day d ,

$R_{r,ap,d}$ = rainfall rate during analysis period ap and day d (in./h), and

$R_{s,ap,d}$ = precipitation rate when snow is falling during analysis period ap and day d (in./h).

If Equation 37-65 is used for analysis periods with falling rain, then the variable R_s should equal 0.0. If it is used for analysis periods with falling snow, then the variable R_r should equal 0.0 and the variable R_s equals the precipitation rate (i.e., it is not a snowfall rate).

The factors obtained from Equation 37-65 apply when there is some precipitation falling. If the pavement is wet and there is no rainfall, then the adjustment factor is 0.95. If the pavement has snow or ice on it and snow is not falling, then the adjustment factor is 0.90.

Segments

The following equation is used to compute the free-flow speed adjustment factor for analysis periods with poor weather conditions. It is used in Step 7 to estimate the additional running time during weather events.

$$f_{s,rs,ap,d} = \frac{1.0}{1.0 + 0.48 R_{r,ap,d} + 1.4 R_{s,ap,d}}$$

Equation 37-66

where

$f_{s,rs,ap,d}$ = free-flow speed adjustment factor for rainfall or snowfall during analysis period ap and day d ,

$R_{r,ap,d}$ = rainfall rate during analysis period ap and day d (in./h), and

$R_{s,ap,d}$ = precipitation rate when snow is falling during analysis period ap and day d (in./h).

If Equation 37-66 is used for analysis periods with falling rain, then the variable R_s should equal 0.0. If it is used for analysis periods with falling snow, then the variable R_r should equal 0.0 and the variable R_s equals the precipitation rate (i.e., it is not a snowfall rate).

The factors obtained from Equation 37-66 apply when there is some precipitation falling. If the pavement is wet and there is no rainfall, then the adjustment factor is 0.95. If the pavement has snow or ice on it and snow is not falling, then the adjustment factor is 0.90.

Step 3: Acquire Demand Adjustment Factors

During this step, the hour-of-day, day-of-week, and month-of-year demand adjustment factors associated with each analysis period are acquired (as identified previously in the traffic demand variation procedure). They are used in Step 6 to estimate the analysis period volumes.

Step 4: Compute Incident Adjustment Factors for Intersections

The following equation is used to compute the saturation flow rate adjustment factor for analysis periods associated with an incident. It is used in Step 5 to estimate intersection saturation flow rate during incidents.

$$f_{ic,int(i),n,m,ap,d} = \left(1.0 - \frac{N_{ic,int(i),n,m,ap,d}}{N_{n,int(i),n,m}} \right) \left(1.0 - \frac{b_{ic,int(i),n,ap,d}}{\sum_{m \in L,T,R} N_{n,int(i),n,m}} \right) \geq 0.10$$

Equation 37-67

Equation 37-68

with

$$b_{ic,int(i),n,ap,d} = 0.58 I_{fi,int(i),n,ap,d} + 0.42 I_{pdo,int(i),n,ap,d} + 0.17 I_{other,int(i),n,ap,d}$$

where

$f_{ic,int(i),n,m,ap,d}$ = saturation flow adjustment factor for incident presence for movement m ($m = L$: left, T : through, R : right) on leg associated with NEMA phase n ($n = 2, 4, 6, 8$) at intersection i during analysis period ap and day d ;

$N_{n,int(i),n,m}$ = number of lanes serving movement m on leg associated with NEMA phase n at intersection i (ln);

$N_{ic,int(i),n,m,ap,d}$ = number of lanes serving movement m blocked by the incident on leg associated with NEMA phase n at intersection i during analysis period ap and day d (ln);

$b_{ic,int(i),n,ap,d}$ = calibration coefficient based on incident severity on leg associated with NEMA phase n at intersection i during analysis period ap and day d ;

$I_{pdo,int(i),n,ap,d}$ = indicator variable for property-damage-only (PDO) crash on leg associated with NEMA phase n at intersection i during analysis period ap and day d (= 1.0 if PDO crash, 0.0 otherwise);

$I_{fi,int(i),n,ap,d}$ = indicator variable for fatal-or-injury crash on leg associated with NEMA phase n at intersection i during analysis period ap and day d (= 1.0 if fatal-or-injury crash, 0.0 otherwise); and

$I_{other,int(i),n,ap,d}$ = indicator variable for non-crash incident on leg associated with NEMA phase n at intersection i during analysis period ap and day d (= 1.0 if non-crash incident, 0.0 otherwise).

Equation 37-67 is applied to each approach traffic movement. For a given movement, the first term of Equation 37-67 adjusts the saturation flow rate based on the number of lanes that are blocked by the incident. If the incident is located on the shoulder or in the lanes associated with another movement m (i.e., $N_{ic} = 0$), then this term equals 1.0.

Equation 37-67 is used for each movement to estimate the saturation flow rate adjustment factor for incidents. If all lanes associated with a movement are closed due to the incident, then an adjustment factor of 0.10 is used. This approach effectively closes the lane but does not remove it from the intersection, as described in the dataset.

Step 5: Compute Saturation Flow Rate for Intersections

During this step, the saturation flow rate for each intersection movement is adjusted using the factors computed in Steps 2 and 4. The weather adjustment factor is applied to all movements at all intersections. The incident adjustment factor is applied only to the movements affected by an incident.

The weather and incident factors are multiplied by the saturation flow rate in the dataset to produce a revised estimate of the saturation flow rate.

Step 6: Compute Traffic Demand Volumes

Adjust Movement Volumes

During this step, the volume for each movement is adjusted using the appropriate hour-of-day, day-of-week, and month-of-year factors to estimate the average hourly flow rate for the subject analysis period. The following equation is used for this purpose.

$$v_{int(i),j,h,d} = \frac{v_{input,int(i),j}}{f_{hod,input} f_{dow,input} f_{moy,input}} f_{hod,h,d} f_{dow,h,d} f_{moy,h,d}$$

Equation 37-69

where

- $v_{int(i),j,h,d}$ = adjusted hourly flow rate for movement j at intersection i during hour h and day d (veh/h),
- $v_{input,int(i),j}$ = movement j volume at intersection i (from HCM dataset) (veh/h),
- $f_{hod,h,d}$ = hour-of-day adjustment factor based on hour h and day d ,
- $f_{dow,d}$ = day-of-week adjustment factor based on day d ,
- $f_{moy,d}$ = month-of-year adjustment factor based on day d ,
- $f_{hod,input}$ = hour-of-day adjustment factor for hour and day associated with v_{input} ,
- $f_{dow,input}$ = day-of-week adjustment factor for day associated with v_{input} and
- $f_{moy,input}$ = month-of-year adjustment factor for day associated with v_{input} .

If a 15-min analysis period is used, then the adjusted hourly flow rate is applied to all four analysis periods coincident with the subject hour h . Equation 37-69 is also used to adjust the volumes associated with each driveway on each segment.

Random Variation Among 15-min Periods

If a 15-min analysis period is used, the analyst has the option of adding a random element to the adjusted hourly volume for each movement and analysis period. Including this random variation provides a more realistic estimate of performance measure variability. However, it ensures that every analysis period is unique (thereby making it less likely that similar scenarios can be found for the purpose of reducing the total number of scenarios to be evaluated). If this option is applied, then the turn movement volumes at each signalized intersection are adjusted using a random variability based on the peak-hour factor. Similarly, the turn movement volumes at each driveway are adjusted using a random variability based on a Poisson distribution.

If the analyst desires to add a random element to the adjusted hourly volume, then the first step is to use the following equation to estimate the demand flow rate variability adjustment factor.

$$f_{int(i),j,h,d} = \frac{1.0 - PHF_{int(i)}}{PHF_{int(i)}} \sqrt{0.25 v_{int(i),j,h,d} \exp(-0.00679 + 0.004 PHF_{int(i)}^{-4})}$$

Equation 37-70

where

$f_{int(i),j,h,d}$ = adjustment factor used to estimate the standard deviation of demand flow rate for movement j at intersection i during hour h and day d ,

$PHF_{int(i)}$ = peak hour factor for intersection i , and

$v_{int(i),j,h,d}$ = adjusted hourly flow rate for movement j at intersection i during hour h and day d (veh/h).

The second step is to use the following equation to compute the randomized hourly flow rate for each movement at each signalized intersection.

Equation 37-71

$$v_{int(i),j,ap,d}^* = 4.0 \times \text{gamma}^{-1}(p = Rf_{ap,d}, \mu = 0.25 v_{int(i),j,h,d}, \sigma = f_{int(i),j,h,d} \sqrt{0.25 v_{int(i),j,h,d}})$$

where

$v_{int(i),j,ap,d}^*$ = randomized hourly flow rate for movement j at intersection i during analysis period ap and day d (veh/h),

$\text{gamma}^{-1}(p, \mu, \sigma)$ = value associated with probability p for cumulative gamma distribution with mean μ and standard deviation σ ,

$Rf_{ap,d}$ = random number for flow rate for analysis period ap and day d ,

$v_{int(i),j,h,d}$ = adjusted hourly flow rate for movement j at intersection i during hour h and day d (veh/h), and

$f_{int(i),j,h,d}$ = adjustment factor used to estimate the standard deviation of demand flow rate for movement j at intersection i during hour h and day d .

Similarly, the following equations are used to compute the randomized hourly flow rates for each driveway. The first equation is used if the adjusted hourly flow rate is 64 veh/h or less. The second equation is used if the flow rate exceeds 64 veh/h.

If $v_{int(i),j,h,d} \leq 64$ veh/h then:

Equation 37-72

$$v_{int(i),j,ap,d}^* = 4.0 \times \text{Poisson}^{-1}(p = Rf_{ap,d}, \mu = 0.25 v_{int(i),j,h,d})$$

Otherwise, then:

Equation 37-73

$$v_{int(i),j,ap,d}^* = 4.0 \times \text{normal}^{-1}(p = Rf_{ap,d}, \mu = 0.25 v_{int(i),j,h,d}, \sigma = \sqrt{0.25 v_{int(i),j,h,d}})$$

where

$v_{int(i),j,ap,d}^*$ = randomized hourly flow rate for movement j at intersection i during analysis period ap and day d (veh/h),

$\text{Poisson}^{-1}(p, \mu)$ = value associated with probability p for the cumulative Poisson distribution with mean μ ,

$Rf_{ap,d}$ = random number for flow rate for analysis period ap and day d ,

$v_{int(i),j,h,d}$ = adjusted hourly flow rate for movement j at intersection i during hour h and day d (veh/h), and

$\text{normal}^{-1}(p, \mu, \sigma)$ = value associated with probability p for a cumulative normal distribution with mean μ and standard deviation σ .

Step 7: Compute Speed for Segments

Additional Delay

During this step, the effect of incidents and weather on segment speed is determined. This effect is added to the HCM dataset as an additional delay incurred along the segment. The variable d_{other} in Equation 17-6 is used with this approach. This additional delay is computed using the following equations.

$$d_{\text{other}, \text{seg}(i), n, ap, d} = L_{\text{seg}(i)} \left(\frac{1.0}{S_{\text{fo}, \text{seg}(i), n, ap, d}^*} - \frac{1.0}{S_{\text{fo}, \text{seg}(i), n}} \right)$$

Equation 37-74

with

$$S_{\text{fo}, \text{seg}(i), n, ap, d}^* = S_{\text{fo}, \text{seg}(i), n} \times f_{s, rs, ap, d} \times \left(1.0 - \frac{b_{ic, \text{seg}(i), n, ap, d}}{N_{o, \text{seg}(i), n}} \right)$$

Equation 37-75

$$b_{ic, \text{seg}(i), n, ap, d} = 0.58 I_{fi, \text{seg}(i), n, ap, d} + 0.42 I_{pdo, \text{seg}(i), n, ap, d} + 0.17 I_{\text{other}, \text{seg}(i), n, ap, d}$$

Equation 37-76

where

$d_{\text{other}, \text{seg}(i), n, ap, d}$ = additional delay for the direction of travel served by NEMA phase n ($n = 2, 6$) on segment i during analysis period ap and day d (s/veh);

$L_{\text{seg}(i)}$ = length of segment i (ft);

$S_{\text{fo}, \text{seg}(i), n}$ = base free-flow speed for the direction of travel served by NEMA phase n on segment i (ft/s);

$S_{\text{fo}, \text{seg}(i), n, ap, d}^*$ = adjusted base free-flow speed for the direction of travel served by NEMA phase n on segment i during analysis period ap and day d (ft/s);

$f_{s, rs, ap, d}$ = free-flow speed adjustment factor for rainfall or snowfall during analysis period ap and day d ,

$b_{ic, \text{seg}(i), n, ap, d}$ = calibration coefficient based on incident severity on leg associated with NEMA phase n at intersection i during analysis period ap and day d ;

$N_{o, \text{seg}(i), n}$ = number of lanes serving direction of travel served by NEMA phase n on segment i (ln);

$I_{pdo, \text{seg}(i), n, ap, d}$ = indicator variable for property-damage-only (PDO) crash in the direction of travel served by NEMA phase n on segment i during analysis period ap and day d (= 1.0 if PDO crash, 0.0 otherwise);

$I_{fi, \text{seg}(i), n, ap, d}$ = indicator variable for fatal-or-injury crash in the direction of travel served by NEMA phase n on segment i during analysis period ap and day d (= 1.0 if fatal-or-injury crash, 0.0 otherwise); and

$I_{\text{other,seg}(i),n,ap,d}$ = indicator variable for non-crash incident in the direction of travel served by NEMA phase n on segment i during analysis period ap and day d (= 1.0 if non-crash incident, 0.0 otherwise).

The delay estimated from Equation 37-74 is added to the “other delay” variable in the dataset to produce a combined “other delay” value for segment running speed estimation.

Segment Lane Closure

If an incident is determined to be located in one or more lanes, then the variable for the number of through lanes on the segment is reduced accordingly. This adjustment is made for the specific segment and direction of travel associated with the incident.

The variable indicating the number of major-street through lanes at each driveway is reduced in a similar manner when the incident occurs on a segment and closes one or more lanes. This adjustment is made for each driveway on the specific segment impacted by the incident.

Step 8: Adjust Critical Left-Turn Headway

Research indicates that the critical headway for left-turn drivers increases by 0.7 to 1.2 s, depending on the type of weather event and the opposing lane associated with the conflicting vehicle. The recommended increase in the critical headway value for each weather condition is listed in Exhibit 37-23.

Exhibit 37-23
Additional Critical Left-Turn
Headway due to Weather

Weather Condition	Additional Critical Left-Turn Headway (s)
Clear, snow on pavement	0.9
Clear, ice on pavement	0.9
Clear, water on pavement	0.7
Snowing	1.2
Raining	0.7

Step 9: Save Scenario Dataset

During this step, the dataset with the updated values is saved for evaluation in the next stage of the reliability methodology. One dataset is saved for each analysis period (i.e., scenario).

5. MEASURING RELIABILITY IN THE FIELD

This section provides a recommended method for measuring reliability in the field. The intent of this section is to provide a standardized method for gathering and reporting travel time reliability for freeways and arterials directly from field sensors, which can be used for validating estimates of reliability produced by the HCM method and for consistently comparing reliability across facilities.

MEASUREMENT OF TRAVEL TIME RELIABILITY

Every current method of measuring travel time reliability in the field involves some form of sampling of the three-dimensional reliability box. The three dimensions of reliability are the study section of the facility, the daily study period, and the reliability reporting period (Exhibit 37-24). For example, one may specify that the travel time reliability be computed for a 1-mi length of freeway during the morning peak hour for all non-holiday weekdays in a year.

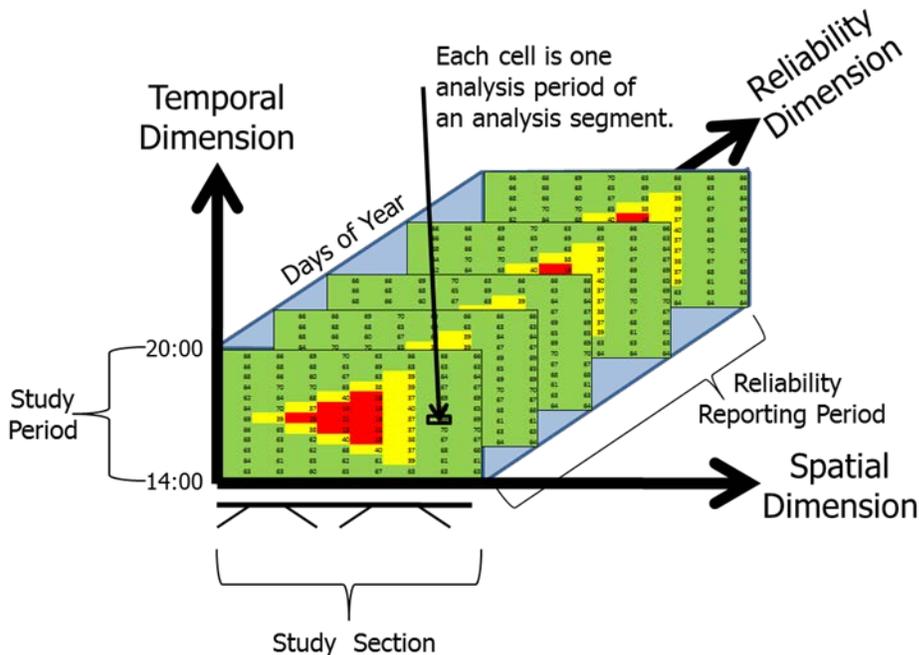


Exhibit 37-24
Three-Dimensional Reliability
Box

DATA SOURCES OF TRAVEL TIME RELIABILITY

Travel time reliability may be measured by recording a sample of the vehicle travel times over a fixed length of facility (probe vehicle method) or by recording the spot speeds of all vehicles as they pass over a set of stationary detectors. This latter method will be called for convenience the "loop detector method," although many technologies are available (radar, video, etc.) in addition to inductive loop detectors for measuring spot speeds.

Loop Detectors and Similar Point Measures of Speed

Loop sensors (or similar point measures of speed) are spaced perhaps as close as one-third to one-half mile apart, but can be much farther apart.

Single loops will measure the time a vehicle spends within the typical 12-ft detection range of the loop and will divide this time by the estimated average vehicle length (supplied by the operator) to arrive at the estimated speed of the vehicle.

Double loops will measure the lag between the time the leading edge of the vehicle arrives at the first loop, and the time when the leading edge arrives at the second loop. The distance between the two loops is divided by the time difference between when the leading edge of the vehicle first arrives at the upstream loop and when it arrives at the downstream loop, thus obtaining the vehicle speed for the short distance between the two loops.

These spot speeds (whether measured using single or dual loops) are often aggregated into average vehicle speeds for 5-min analysis periods.

For study sections where multiple loop detector stations are present, the speeds from the detectors may be simply averaged, or they may be length weighted averaged (where each detector is assumed to represent a different length of the facility). The study period used to compute the average may be offset by the average travel time of vehicles as they move from one segment to the next.

Probe Vehicles

Electronic toll tag or Bluetooth readers can be deployed at certain segments of freeway so that time stamps of vehicles crossing at these locations can be tracked. When a vehicle with a toll tag or a discoverable Bluetooth device crosses locations with readers, identification of the same vehicle can be matched with different time stamps and corresponding locations. Then the travel time between a pair of toll tag reader locations can be obtained.

It is necessary to have a filtering algorithm that removes vehicles from the sample that take an excessive amount of time to show up at the downstream detector. This is to remove vehicles that leave the facility to stop for errands in between the two detectors. The closer together the two readers, the tighter the filtering criterion can be.

Unreasonably high travel times obtained from toll tag readers should be discarded by setting a cutoff point at the 99th percentile of the raw data. If after filtering, the data still show a mean travel time greater than the 95th percentile travel time (an indication that some vehicles stopping for errands are still in the dataset) then the highest travel time point should be removed, and the removal process repeated until the mean travel time falls below the 95th percentile travel time.

Comparison of Sampling Methods

Loop detectors take a vertical sample of the facility time-space diagram, while probe vehicles (ETC) detectors take a diagonal sample of the facility time-space diagram (compare Exhibit 37-25 and Exhibit 37-26).

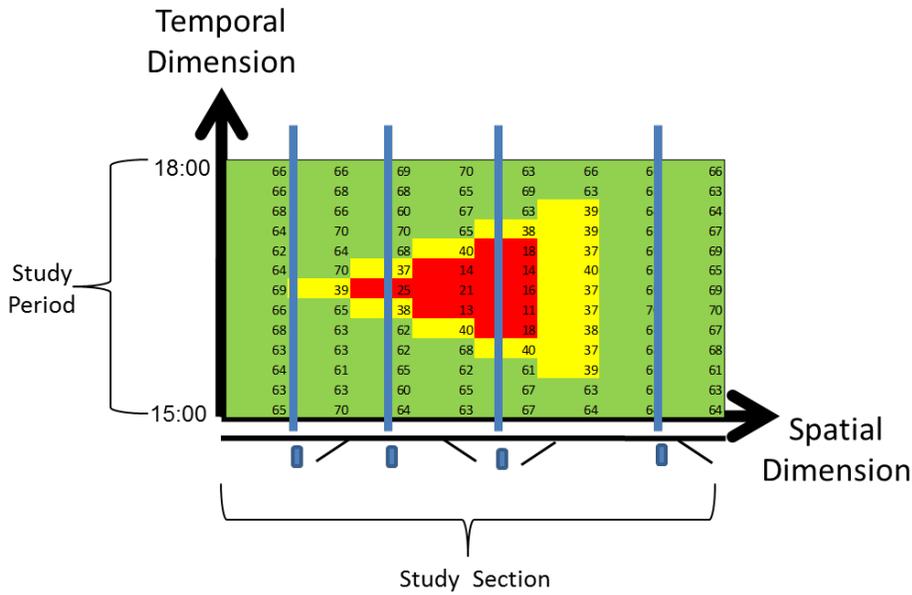


Exhibit 37-25
Spot Speed (Vertical)
Sampling of Loop Detectors

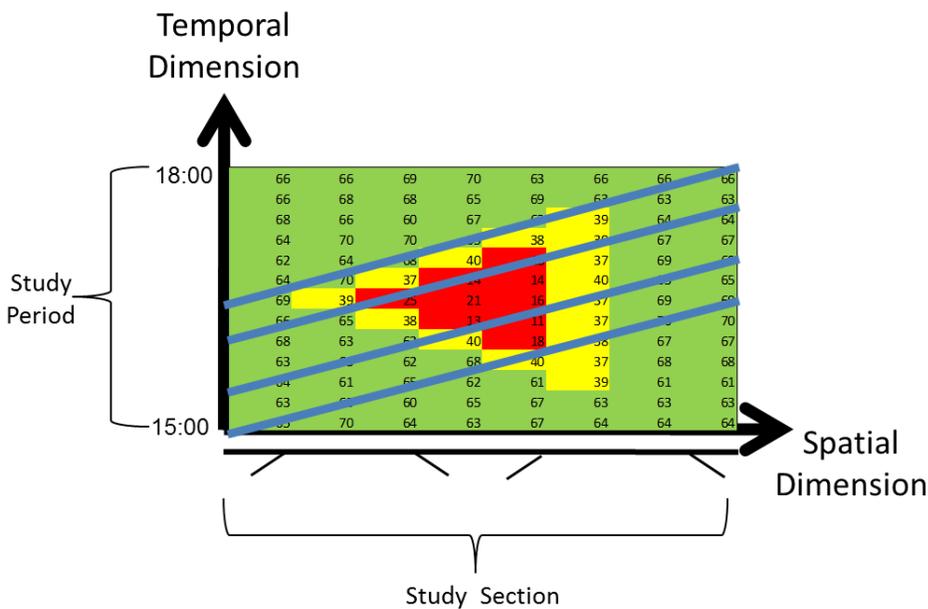
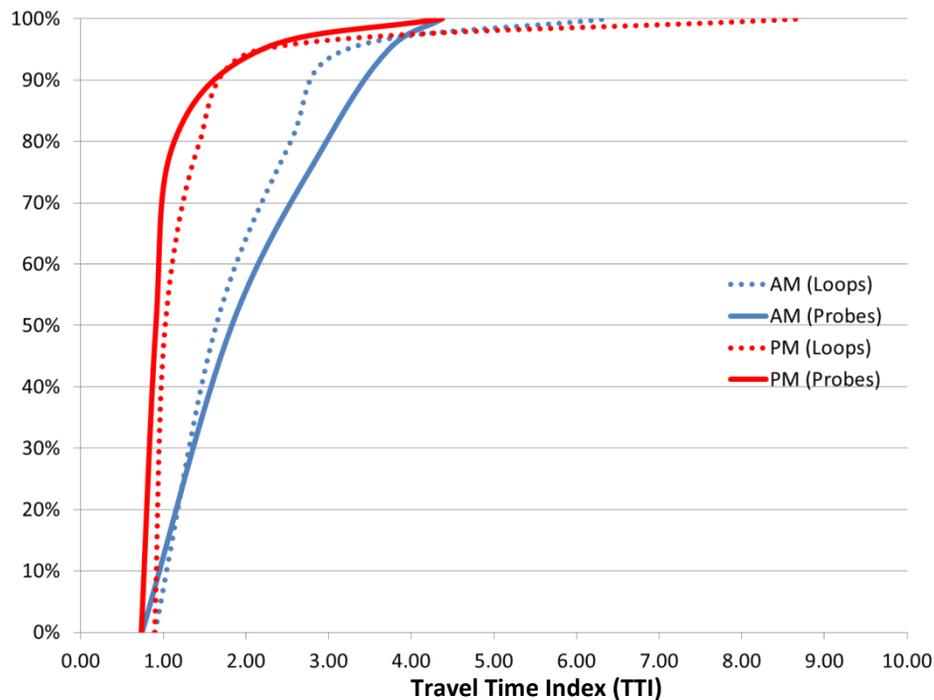


Exhibit 37-26
Time-Space (Diagonal)
Sampling of Probe Vehicle
Detectors

The two measurement methods, since they sample the three-dimensional reliability space differently, will produce slightly different estimates of the travel time reliability distribution, as illustrated for one freeway in Exhibit 37-27. However, the differences between the methods will generally be less than the differences in reliability between different peak periods.

Exhibit 37-27
Comparison of Loop Detector
and Probe Cumulative Travel
Time Distributions



Source: Kittelson & Associates, Inc.

Note: I-80 westbound, Contra Costa County, California.

Each method has its strengths and weaknesses and neither method is always the best. A dense network of loop detectors may produce better estimates than a sparse network of toll tag readers. The reverse may also be true. Thus the choice of method is contingent on the density of the detection available for each method.

RECOMMENDED METHOD FOR COMPUTING RELIABILITY USING LOOP DETECTORS

The recommended method for computing travel time reliability statistics for freeways using loop detectors or other stationary sensors of spot speeds is described below. Because of the highly varying nature of speeds by distance from signal on urban streets, the loop detector method is *not* recommended for urban streets.

1. *Define Reliability Study Bounds.* Select facility direction, length, study period, and reliability reporting period. The recommended reliability reporting period should be at least 150 days and preferably closer to 250 days.
2. *Download Data.* Download lane-by-lane vehicle speeds and volumes aggregated or averaged to 5-min periods for all mainline speed detectors for selected study direction, within selected facility length, study period, and for all days included in reliability reporting period.

3. *Quality Check Data.*
 - a. If system estimates data to fill in for gaps in detector data (detectors down), then remove all data with less than 70% observed rating.
 - b. Remove unrealistic speeds from data set. (Use local knowledge to determine what is unreasonable. In absence of specific local knowledge, use these two criteria to remove data: average speeds greater than 120% of the posted speed limit; average speeds observed for less than 5 veh).
 - c. Gaps in data are treated as non-observations.
4. *Compute 5-min VMTs.*
 - a. For each detector station, identify the length of facility represented by the detector. This is usually half the distance to the upstream detector station plus half the distance to the downstream detector, but it can be a different value based on local knowledge of the facility.
 - b. Sum up volumes across all lanes at detector station for 5-min time periods.
 - c. Neglect periods when the detector is not functioning.
 - d. $VMT(t,d) = V(t,d) \times L(d)$ where: VMT = vehicle-miles traveled during time period t measured at detector station d ; L = length represented by detector station d (mi), V = sum of lane volumes (veh) measured at detector station d during time period t .
5. *Compute 5-min VHTs.*
 - a. $VHT(t,d) = VMT(t,d) / S(t,d)$ where: VHT = vehicle-hours traveled during time period t measured at lane detector station d ; S = arithmetic average speed of vehicles (mi/h) measured during time period t , at lane detector station d .
 - b. Neglect periods when the detector is not functioning.
6. *Compute Free-Flow Speed for Facility.*
 - a. Select a non-holiday weekend.
 - b. For each detector, obtain 5-min speeds for 7 a.m. to 9 a.m. on a typical weekend morning.
 - c. Neglect periods when the detector is not functioning.
 - d. Quality control for excessively high speeds or excessively low volumes as explained earlier.
 - e. Identify the 85th percentile highest speed. That is the free-flow speed for the detector.
 - f. Convert speed to segment travel times.
 - g. Sum segment times to obtain facility free-flow travel times.

7. *Compute TTIs for Time Periods.*

- a. The TTI for each 5-min period at each detector is computed as follows:

$$TTI(t, d) = \frac{\sum_a VHT(t, d)}{\sum_a VHTFF(t, d)}$$

where $VHT(t, d)$ is vehicle-hours traveled for prevailing speeds during time t at detector d and $VHTFF(t, d)$ is vehicle-hours traveled at theoretical free-flow speeds for detector d during time t .

8. *Compute Mean TTI for Facility.*

$$TTI = \frac{\sum_{t,d} VHT(t, d)}{\sum_{t,d} VHTFF(t, d)}$$

9. *Compute PTI for Facility.*

$$PTI = 95\text{th}\% TTI(t)$$

RECOMMENDED METHOD FOR COMPUTING RELIABILITY USING PROBE VEHICLES

The recommended method for computing travel time reliability statistics for freeways and arterials using probe vehicles and Bluetooth, toll-tag, or license plate readers is described below. The instructions below assume the data are obtained from a commercial vendor of historic traffic message channel (TMC) segment speed data.

1. *Define Reliability Study Bounds.* Select the facility direction, length, study period, and reliability reporting period. The recommended reliability reporting period should be at least 150 days and preferably closer to 250 days.
2. *Download Data.* Download TMC segment speeds (or travel times if using Bluetooth or toll-tag reader data) aggregated or averaged to 5-min (or similar) periods for all mainline segments for the selected study direction and selected facility length, for all study periods and days included in the reliability reporting period.
3. *Quality Check Data.*
 - a. Remove travel times that fall in the top 99th percentile of the data. This removes trips that stop or leave the facility for errands and then return.
 - b. If working with travel time data (e.g., Bluetooth or toll-tag reader data), convert data to speeds for error checking purposes.
 - c. Remove unrealistic speeds from data set. (Use local knowledge to determine what is unreasonable. In the absence of specific local knowledge, remove data with average speeds greater than 120% of the posted speed limit.)

4. *Compute Facility Travel Times for Each Analysis Period.*
 - a. For each TMC (or Bluetooth/toll-tag reader) segment, identify its length in miles (to the nearest 0.01 mi).
 - b. Divide the segment length by speed to obtain the segment travel time for each analysis period (skip this step if using Bluetooth/toll-tag travel time data).
 - c. Sum the segment travel times to obtain the facility travel time for each time period.
5. *Compute Free-Flow Speed for Facility.*
 - a. If confident in the segment reference speed provided by the commercial vendor; that can be used for the free-flow speed. If not confident, perform the following steps.
 - b. Select a non-holiday weekend.
 - c. For each segment, obtain speeds for 5-min time periods for 7 a.m. to 9 a.m. on a typical weekend morning.
 - d. Quality control for excessively high speeds or travel times as explained earlier.
 - e. Identify the 85th percentile highest speed. That is the free-flow speed for the segment.
 - f. Convert the segment speed to segment travel times (segment length divided by segment speed).
 - g. Sum the segment times to obtain facility free-flow travel times.
6. *Compute TTIs for Time Periods.*
 - a. The TTI for each 5-min time period is the ratio of the mean facility travel time for the 5-min period to the free-flow travel time. It is computed as follows:

$$TTI(t) = \frac{\sum_d VHT(t, d)}{\sum_d VMT(t, d)}$$

7. *Compute Mean TTI for Facility.*

$$TTI = \frac{\sum_{t,d} VHT(t, d)}{\sum_{t,d} VMT(t, d)}$$

8. *Compute PTI for Facility.*

$$PTI = 95\text{th}\% TTI(t)$$

Additional example problems are provided in Chapter 36.

Exhibit 37-28
Example Problem 1: Study Freeway Facility

6. EXAMPLE PROBLEM

EXAMPLE PROBLEM 1: EXISTING FREEWAY RELIABILITY

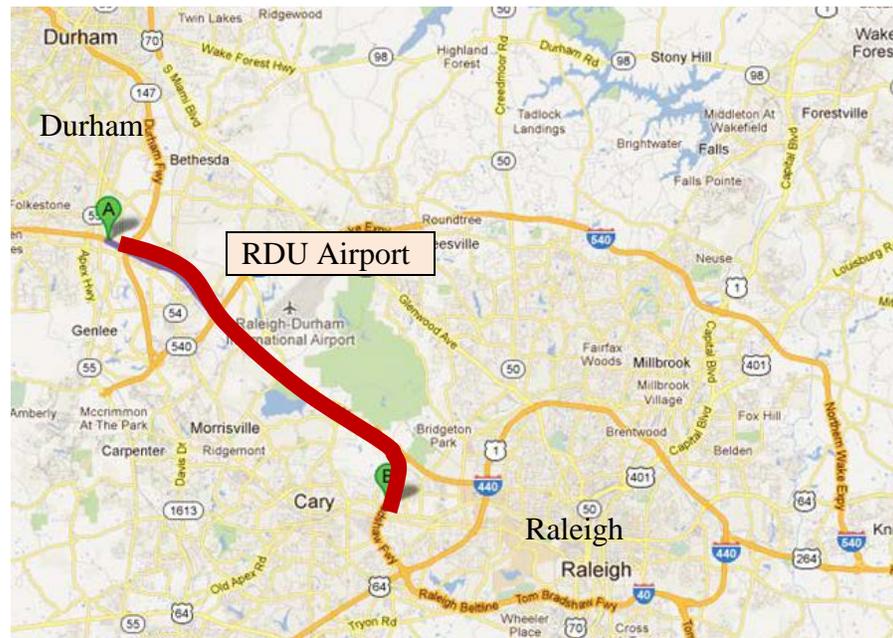
Objective

This example problem illustrates the process of:

1. Calculating reliability statistics for a freeway facility using the minimum required data for the analysis,
2. Identifying key reliability problems on the facility, and
3. Diagnosing the causes (e.g., demand, weather, incidents) of reliability problems on the facility.

Site

The study freeway facility is a 12.5-mi portion of eastbound I-40 between Durham and Raleigh, NC, bounded by NC-55 to the west and NC-54 to the east (Exhibit 37-28). The eastbound direction is most heavily utilized by commuters on weekdays, with a peak hour of 5 p.m. to 6 p.m. The posted speed limit is 65 mi/h. A weaving section near the downstream end of the facility creates a recurring bottleneck during peak demand levels.



Source: © Google Maps, 2012.

Minimum Required Data Inputs

The data listed below are required to perform a reliability analysis of a freeway facility. Additional desirable data are also identified, but this example problem assumes that the additional desirable data are not available. Instead, this example illustrates the use of defaults and look-up tables to substitute for the desirable data.

- Data required for an HCM freeway facility analysis (Chapter 10):
 - Facility volumes by 15-min analysis periods (time slices) for a single day's peak period.
 - *Desirable: single day's peak period facility travel times for calibrating a traditional HCM 2010 operations analysis model for the facility.*
 - Facility geometry and controls by analysis segment and by analysis period (if controls vary by analysis period) for the study period (if controls or geometry vary by time of day, day of week, or month of year).
- Data required to estimate demand variability:
 - AADT, directional factor (D), and peak period demand profiles (K -factors)
 - *Desirable: archived peak period mainline volume counts for previous year.*
- Data required to estimate incident frequencies:
 - Collision reports for the prior 3-year period.
 - *Desirable: Detailed incident logs including frequency, duration, and location of incidents for similar period.*
- Data required to estimate weather frequencies:
 - Weather reports for at least the prior 3-year period.
 - *Desirable: 10-year weather data from a nearby weather station.*
- Optional extra data for calibrating estimates:
 - Facility travel times (or spot speeds) and volumes by 15-min analysis periods (time slices) for the target study period (peak periods, days of weeks, months of year, etc.).

Computational Steps

This example problem proceeds through the following steps:

1. Scoping the bounds of the reliability analysis:
 - a. Establishing the analysis purpose, scope, and approach;
 - b. Selecting an appropriate study period;
 - c. Selecting an appropriate reliability reporting period; and
 - d. Selecting appropriate reliability performance measures and thresholds of acceptable performance.
2. Coding the HCM facility operations analysis:
 - a. Identifying the sources of unreliability to be analyzed;
 - b. Coding base conditions; and
 - c. Coding alternative datasets, if any.
3. Estimating the demand variability profile.
4. Estimating severe weather frequencies.

5. Estimating incident frequencies.
6. Generating scenarios and the probabilities of their occurrence.
7. Applying the Chapter 10 freeway facility method.
8. Performing quality control, error checking, and validation.
9. Calculating performance measures.
10. Diagnosing the causes of unreliable performance.
11. Interpreting results.

Step 1: Scope the Bounds of the Reliability Analysis

While most professional engineers and planners are already well trained in scoping a traditional highway capacity analysis, travel time reliability introduces some extra considerations not part of a traditional capacity analysis:

- Selecting an appropriate *study period* for reliability (hours of day) and an appropriate *reliability reporting period* (days of week, months of year).
- Selecting appropriate reliability performance measures according to the agency's reliability objectives and the facility type.
- Selecting thresholds of acceptable performance.

A reliability analysis has much greater data and computational demands than a traditional HCM operations analysis. Therefore, it should be tightly scoped to ensure the analyst has the resources to complete the analysis. Furthermore, a loosely scoped analysis that provides more days and hours than needed runs the risk of “washing out” the reliability results by mixing in too many hours or days of free-flow conditions into the analysis.

Purpose

To focus the analysis, it is important to identify the purpose for performing the reliability analysis. In this example, the purpose of performing the reliability analysis of existing conditions is to:

- Determine if the facility is experiencing significant reliability problems.
- Diagnose the primary causes of the reliability problems on the facility so that an improvement program can be developed for the facility.

Determining the Reliability Analysis Box

The reliability reporting period has three dimensions: (a) the geometric limits of the facility to be evaluated (the *study section*), (b) the period(s) within the day when the analysis is to be performed (the *study period*), and finally (c) the days of the year over which reliability is to be computed and reported (the *reliability reporting period*). The result is a spatial–temporal reliability box (see Exhibit 37-24) within which reliability is computed.

The reliability box should be dimensioned so that it includes all of the recurring congestion (congestion occurring under recurring demand conditions, in fair weather, without incidents) of interest for the analysis. This favors a large reliability box. However, the larger the reliability box, the greater the number of

instances of free-flow conditions, which will tend to mask or wash out the reliability problems.

In this example, an examination of the facility over several days has determined the general spatial and temporal boundaries of congestion on the facility under fair weather, non-incident conditions. The selected study period was the 6-h-long weekday afternoon peak period (2 p.m. to 8 p.m.), and the 12.5-mi facility length between NC-55 and NC-54 (corresponding to 34 HCM analysis segments). All of the instances where speeds regularly drop below 40 mi/h are encompassed within the selection study section and study period. Exhibit 37-29 shows an example of the speed profile when an incident occurs in the furthest downstream segment on the facility.

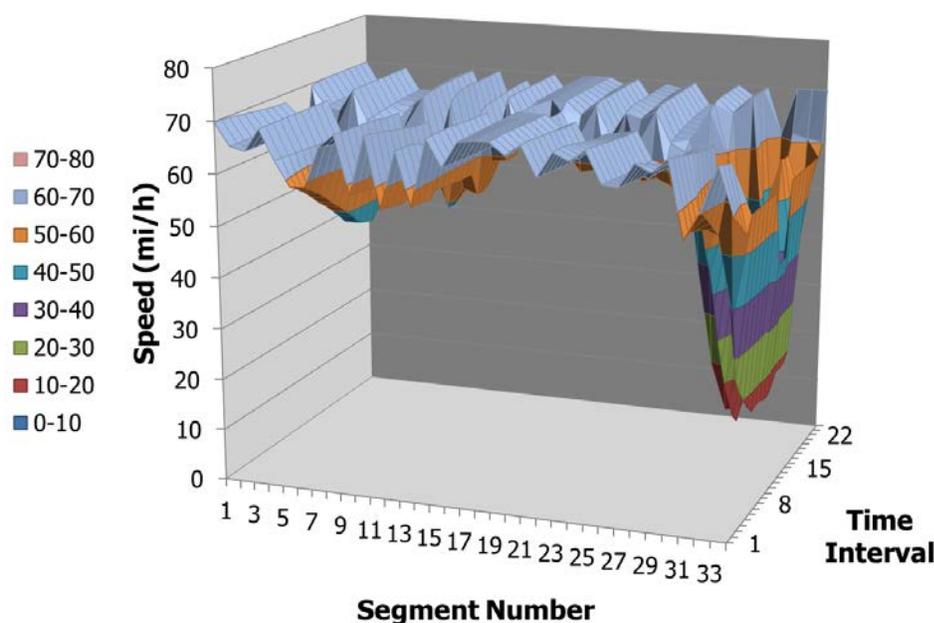


Exhibit 37-29

Example Problem 1: Sample Congested Speed Profile on I-40

Once the study section length and the study period have been selected, the next step is to determine how many (and which) days of the year to compute the reliability for (the reliability reporting period). The objective of setting the reliability reporting period is to focus the analysis on days when reliability is a concern. The reporting period should include enough days so that the probability of encountering a significant number and range of incident types is high. A minimum of 100 days is recommended for the reporting period, although a full-year analysis is preferred.

Thus, for this example, weekdays for a full year were selected for the reliability reporting period. At 5 weekdays per week, 52 weeks plus one day per year, there are 261 weekdays per year (including holidays). Holidays may be excluded from the reliability reporting period if they result in lower than normal p.m. peak period demands. (In this case, holidays were not deemed to be a significant factor affecting reliability, and were therefore included in the reliability analysis.)

If an agency wishes to focus on non-weather effects and avoid vacation effects, then a single season may be selected, rather than a full year. The selection of the appropriate reliability reporting period hinges on the agency's purpose for the analysis.

Selecting Reliability Performance Measures

For instructional purposes, all of the reliability performance measures shown in Exhibit 37-30 will be computed. However, for a typical application, one or two performance measures most useful to the agency's analysis purpose are recommended to be selected.

Exhibit 37-30

Example Problem 1: Reliability Performance Measures to be Evaluated

Measure	Definition
Mean TTI	Mean travel time divided by free-flow travel time
Planning Time Index (PTI)	95th percentile travel time divided by free-flow travel time
80th percentile TTI	80th percentile travel time divided by free-flow travel time
Semi-standard deviation	One-sided standard deviation, referenced to free-flow
Failure/on-time	Percent of trips less than 40 mi/h
Standard deviation	Usual statistical definition
Misery index	Average of top 5% of travel times divided by free-flow travel time
Reliability rating	Percentage of VMT at a TTI less than 1.33

Since all performance measures are derived from the same travel time distribution (see Exhibit 36-5 in Chapter 36), once an agency has picked one or two measures for the reliability analysis, additional measures do not bring significant new information to the results. In that sense, it is most important that the agency selects performance measures consistently across different reliability analyses, allowing agency staff and stakeholders to begin developing an understanding of these metrics.

In this example, the agency could pick the mean TTI so that average performance could be evaluated (the mean is useful for computing total benefits later). As an indicator of reliability, the agency could pick the 80th percentile TTI or the PTI.

Selecting Thresholds of Acceptable Performance

Ideally, an agency has already developed its own thresholds of acceptable reliability performance based on locally collected data. However, in this case, the agency responsible for the freeway has not yet assembled sufficient data on the reliability of its own facilities to have confidence in setting its own standards. Consequently, two standards of performance will be evaluated in this example problem as part of the reliability assessment.

The first standard will be determined by comparing performance of the I-40 facility to other facilities in the SHRP 2 L08 dataset. The agency uses the values in Exhibit 37-1 to select acceptable mean TTI and PTI values as its desired reliability performance thresholds. For example, the operating agency may select a performance threshold to be more reliable than the worst 10% of U.S. urban freeway facilities studied for this project. Thus, if the mean TTI for the facility is computed to be greater than 1.93, then the facility's reliability will be considered unacceptable. Similarly, if the computed PTI exceeds 3.55, that will also be considered unacceptable.

The second standard is set based on the agency's congestion management goal of operating its freeways at 40 mi/h or better during the majority of the peak periods within the year. This particular standard requires that a modified travel time performance index, called the *Policy Index* (PI) be computed that uses the agency's 40 mi/h target speed in place of the free-flow speed.

$$PI = \frac{\text{mean travel time}}{\text{travel time at 40 mi/h}}$$

Since the agency's goal is for the mean annual peak period speed on the facility to be 40 mi/h or higher, then if the PI exceeds 1.00, the reliability of the facility will be considered unacceptable.

Step 2: Code the HCM Facility Operations Analysis

Selecting Reliability Factors for Evaluation

The major causes of travel time reliability problems are demand surges, weather, incidents, special events, and work zones. Evaluating all possible causes of reliability puts a significant strain on analytical resources, so it is recommended that rarer causes of unreliability be excluded from the reliability analysis. In addition, the purpose of the analysis may suggest that some causes can be bundled together.

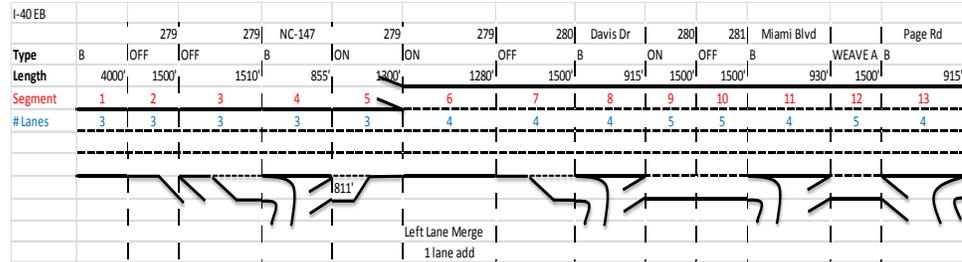
The study facility in this case is large and adjacent special generators do not significantly affect operations during the selected study period (most events are on weekends). Consequently, the effects of special events do not need to be evaluated separately and can be bundled in with other causes of surges in demand. Similarly, work zones are not planned to operate during weekday peak periods on the facility in the analysis year, so work zones can be excluded from the reliability analysis.

Coding Base Conditions

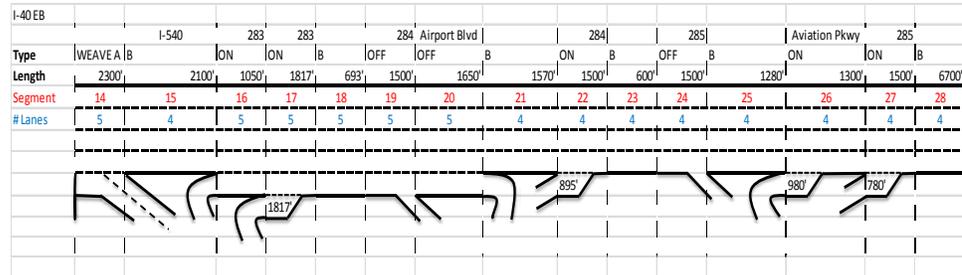
The base HCM analysis input file (the seed file) was coded for the selected study section and study period using the procedures and guidance contained in Chapters 10–13. Demands, geometries, and free-flow speed were obtained for a single, typical, fair weather, non-incident, non-holiday, weekday p.m. peak period (2 p.m. to 8 p.m.). Exhibit 37-31 shows the geometry of the study section of the facility. Exhibit 37-32 shows a portion of the input entries for the seed file.

Mainline volumes were obtained from side-fire radar stations spaced roughly 1.5 mi apart. Ramp volumes were counted for two weeks using portable tube counters. A typical fair-weather weekday when daily traffic was close to the annual average daily traffic was selected from the two-week count period. Default values of 5% trucks, 0% recreational vehicles, and 0% buses were used to account for heavy vehicles.

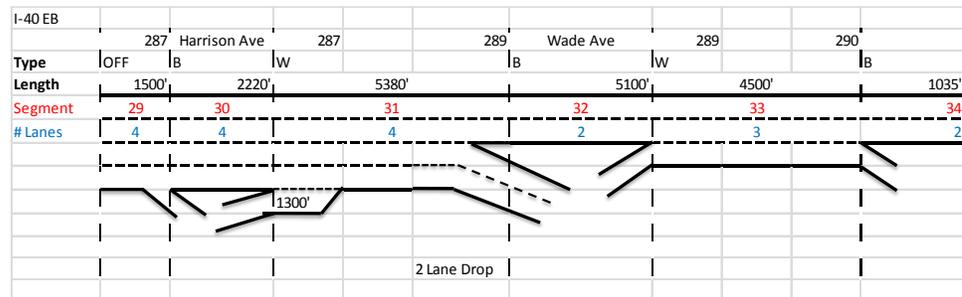
Exhibit 37-31
 Example Problem 1: Study
 Section Geometry



Section A



Section B



Section C

There were no extended grades in excess of 2% for longer than 0.5 mi on the facility (see page 11-15), and the facility has a general level vertical profile, so a general terrain category of “level” was used to characterize the vertical geometry of the facility.

Segment lengths and number of lanes were obtained by field inspection or Google aerial photos. Lane widths are a standard 12 ft. The free-flow speed was estimated using Equation 11-1.

Release Date: Release February 2013								
Project Name: I-40 EB								
SEGMENT NUMBER :	1	2	3	4	5	6	7	8
SECTION NUMBER :	1	2	3	4	5	6	7	8
SEGMENT LABEL :	S01	S02	S03	S04	S05	S06	S07	S08
Type (B, ONR, OFR, R, or W)	B	OFR	OFR	B	ONR	ONR	R	OFR
Length (ft)	4000	1500	1500	855	1300	1280	220	1280
Number of Lanes	3	3	3	3	3	3	4	4
FF Speed (Mi/hr)	70	70	70	70	70	70	70	70
Segment Demand (vph)	3,427	3,427	3,359	3,017	3,396	4,889	4,889	4,889
Capacity Adjustment Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Origin Demand Adjustment Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Destination Demand Adjustment Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Speed Adjustment Factor	1.00	1.00	1.00	1.00	1.00	1.00	1.00	1.00
% Trucks	5.0	5.0	5.0	5.0	5.0	5.0	5.0	5.0
% RV's	0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
On-Ramp Demand (vph)					379	1,493		
On-Ramp % Trucks					5	5		
On-Ramp % RV's					0	0		
Off-Ramp Demand(vph)	68	342						190
Off-Ramp % Trucks	5	5						5
Off-Ramp % RV's	0	0						0
Acc/ Dec Lane Length (ft)	300	300			800	1280		300
Number of Lanes on Ramp	1	1			1	1		1
Ramp on Left or Right (L / R)	Right	Right			Right	Left		Right
Ramp FFS (mi/hr)	45	45			45	55		45
Ramp Metering Rate (vph)					2100	2100		

Exhibit 37-32

Example Problem 1: Sample Freeway Input Entries for Seed File

Coding Alternative Datasets

As there is no need to account for special events or work zones, no alternative datasets need to be created. If there had been a need for them, they would have been developed in the same way as the base dataset, with appropriate modifications to the input data to reflect changes in demand, geometry, and traffic control.

Step 3: Estimate the Demand Variability Profile

The total number of scenarios that must be evaluated significantly affects the processing time and the time required by the analyst to analyze the results. The number of scenarios is the product of the number of demand levels, weather levels, and incident levels selected for evaluation. Thus any reduction in the number of unnecessary demand, weather, and incident levels needed for the reliability analysis will result in significant processing and evaluation time savings for the analysis.

Based on examination of local data on I-40 demand variability over the course of a year (Exhibit 37-33), it was determined that weekday demand variability over the year at the site could be adequately represented by three demand patterns (Monday–Wednesday, Thursday, Friday) and four month types grouped by the major seasons of the year (December–February, March–May, June–August, September–November). Thus it was possible to consolidate potentially 60 different demand levels (5 weekdays times 12 months) into 12 demand levels (3 weekday patterns by 4 month types). Days and months with similar ratios of monthly average ADT (average daily traffic) to AADT (annual average daily traffic) for a given demand pattern were grouped together. All entries were normalized to a Monday in January. In the event such detailed data are unavailable, the user can refer to the national urban or rural default demand ratios provided in Exhibits 36-22 and 36-23, respectively, in Chapter 36.

Exhibit 37-33

Example Problem 1: Demand Ratios for I-40 Case Study (ADT/Mondays in January)

Month	Day of Week				
	Monday	Tuesday	Wednesday	Thursday	Friday
January	1.00	1.03	1.04	1.05	1.08
February	0.94	1.01	1.04	1.09	1.14
March	1.04	1.07	1.06	1.11	1.17
April	1.07	1.09	1.10	1.16	1.22
May	1.08	1.11	1.11	1.16	1.21
June	1.08	1.09	1.07	1.14	1.18
July	1.08	1.07	1.10	1.15	1.18
August	1.05	1.05	1.06	1.09	1.16
September	1.02	1.02	1.02	1.07	1.15
October	1.05	1.05	1.07	1.11	1.16
November	0.97	1.00	1.04	1.08	1.07
December	0.97	0.96	0.99	0.92	1.01

Entries in Exhibit 37-33 are ADT demand adjustments for a given combination of day and month relative to ADT for a Monday in January. Exhibit 37-34 shows the consolidated table of demand ratios for the example problem.

Exhibit 37-34

Example Problem 1: Consolidated Demand Ratios for I-40 Case Study

Season	Monday–Wednesday	Thursdays	Fridays	Average
Winter	0.9969	1.0202	1.0765	1.0398
Spring	1.0813	1.1435	1.1989	1.0443
Summer	1.0689	1.1264	1.1767	1.0916
Fall	1.0267	1.0878	1.1281	1.1272
Average	1.0435	1.0945	1.1450	1.0744

Note that the average demand ratio for this table is greater than one, which is a result of the base dataset demands being lower than an average day of the year. Since all factors in the above table will be applied as multipliers to the base dataset demand, the relative factors are more pertinent to the analysis than their absolute values.

The probability of each demand level is computed based on the number of days represented by the consolidated demand level divided by the total number of days in the reliability reporting period (5 weekdays times 52 weeks, plus one day, or 261 days) (Exhibit 37-35). Deviations from 25% probability for the seasons, and 5% for the individual demand patterns are due to differing number of days in the months and differing numbers of weekdays in each month. This particular computation is for the calendar year 2010.

Exhibit 37-35

Example Problem 1: Percent Time of Year by Season and Demand Pattern

Season	Monday–Wednesday	Thursdays	Fridays	Average
Winter	13.903%	4.887%	5.255%	24.045%
Spring	15.179%	4.933%	4.933%	25.045%
Summer	15.475%	5.022%	5.022%	25.519%
Fall	15.246%	5.066%	5.079%	25.391%
Average	59.804%	19.907%	20.289%	100.000%

Step 4: Estimate Severe Weather Frequencies

Exhibit 10-15 identifies five weather types (rain, snow, temperature, wind, and visibility) with varying intensity levels that affect the capacity of freeways. Some of these categories or intensity levels have negligible effect on freeway capacities (4% or less effect) and are consequently neglected in the reliability analysis. Based on this criterion, rain under 0.10 in./h, temperature events above -4°F, and all wind events are consolidated into the “non-severe” weather category because of their negligible effects on capacity.

A 10-year weather history of NWS METARS data was obtained for the nearby Raleigh-Durham Airport from Weather Underground. The data were filtered to eliminate “unknown” (-9999) conditions. The time between reports was calculated to obtain the duration of each weather report and to account for missing reports. The data were then classified into the weather categories defined in Exhibit 36-4 in Chapter 36.

The percent time during the reliability reporting period that each of the weather categories are present was computed by dividing the total number of minutes for each weather category observed in the prior 10 years during the reliability reporting period by the total number of minutes within the reliability reporting period (Exhibit 37-36). The total number of minutes within the reliability reporting period for the 10-year period of weather observations (939,600 min) was computed for this example by multiplying the 6-h study period per day by 60 min per hour by 261 weekdays per year (5 weekdays per week times 52 weeks per year plus 1 day) by 10 years. In cases where multiple weather categories are present (e.g., poor visibility during a snow event), the more severe condition (the one most impacting capacity) is assumed to control and the event is assigned that weather category.

Month	Rain		Snow				Cold	Visibility			Non-Severe Weather
	Med.	Heavy	Light	Light-Med.	Med.-Heavy	Heavy	Severe	Low	Very Low	Min.	
January	1.97%	0.00%	5.91%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	92.12%
February	2.72%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	2.17%	0.00%	0.00%	95.11%
March	0.51%	0.00%	1.01%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	98.48%
April	0.00%	0.54%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	99.46%
May	1.95%	1.95%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	96.10%
June	0.51%	0.51%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	98.99%
July	0.50%	0.50%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	99.00%
August	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%
September	4.26%	0.53%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	95.21%
October	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%
November	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	100.00%
December	0.00%	0.00%	7.81%	0.49%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	91.71%
Year	1.03%	0.34%	1.23%	0.04%	0.00%	0.00%	0.00%	0.18%	0.00%	0.00%	97.18%

Notes: Med. = Medium, Min. = Minimal.

Entries are minutes of identified weather type divided by total minutes of weekday study periods (weekdays, 6-h p.m. peak in this example) for that month. Monthly and annual percentages total to 100% for each month and for the full year.

Weather categories with less than 0.1% probability for a given month in the 10-year weather history were dropped from further consideration to manage the number of scenarios. Based on this criterion, severe cold, medium-heavy and heavy snow, and very low and minimal visibility were dropped and the probabilities of all remaining categories re-normalized to add up to 100%. The final set of six weather categories and intensity levels selected for this example problem are shown in Exhibit 37-37 along with their estimated probabilities.

<http://www.wunderground.com/history/>

Exhibit 37-36

Example Problem 1: Percent Time Weather Categories Present on I-40 by Month

Exhibit 37-37

Example Problem 1:
Estimated Percent Time
Weather Events Present on I-
40 by Season

Season	Medium Rain	Heavy Rain	Light Snow	LM Snow	Low Visibility	Normal Weather	Total
Winter	1.496%	0.000%	4.745%	0.175%	0.679%	92.905%	100.000%
Spring	0.797%	0.802%	0.352%	0.000%	0.000%	98.049%	100.000%
Summer	0.335%	0.335%	0.000%	0.000%	0.000%	99.330%	100.000%
Fall	1.440%	0.180%	0.000%	0.000%	0.000%	98.380%	100.000%
Total	1.010%	0.332%	1.229%	0.042%	0.163%	97.223%	100.000%

Note: LM = light to medium.

Seasonal weather probabilities are assumed to apply identically to all demand patterns within the season. (Weather is assumed to be independent of demand pattern within the season.)

Step 5: Estimate Incident Frequencies

Exhibit 10-17 in Chapter 10 identifies the capacity effects of five incident types (shoulder disablement, shoulder accident, one lane blocked, two lanes blocked, and three lanes blocked). The shoulder disablement category was dropped for this example problem because its capacity effects are 1% for facilities with 3 or more lanes, such as the facility in this example problem.

The HCM analysis method, like all methods limited to a single facility, cannot produce meaningful results for complete facility closures, since any methodology confined to a single facility cannot predict demand rerouting to other facilities. Therefore, the evaluation of incidents in this example is limited to incidents that maintain at least one lane open to traffic. The facility is mostly four lanes in one direction, but there are some segments with only two or three lanes.

In this example, generalized crash data were available, but reliable incident logs that indicated incident type by number of lanes closed were not. Five years of crash data were obtained for the 12.5-mi long eastbound direction of I-40. The data indicated that this portion of I-40 experiences an average of 164.5 crashes per 100 million VMT.

The crash rate for this facility then was expanded to incidents by lane and shoulder closure type using an expansion factor. A local study comparing shoulder and lane closure incidents to reported crashes found that there were approximately seven incidents involving shoulder or lane closures for every reported crash on I-40.

The expected number of incidents I by month m for the facility is computed as follows:

Equation 37-77

$$I(m) = \frac{CR \times ICR \times VMT(\text{seed}) \times DM(m)}{100 \times 10^6 \times SFDM}$$

where

I_m = Expected number of incidents in month m in the subject direction of travel (incidents),

CR = Reported crash rate (crashes per 100 million VMT),

ICR = Ratio of incidents to reported crashes (incidents/crash),

$VMT(\text{seed})$ = Seed file VMT on facility in subject direction during study period (VMT),

$DM(m)$ = Demand multiplier for month m (unitless), and

$SFDM$ = Seed file demand multiplier, the ratio of seed file study period demand to AADT for the study period (unitless).

The estimated number of incidents is split into severity types and mean durations using the values shown in Exhibit 37-38.

Severity	Shoulder Closed	1 Lane Closed	2 Lanes Closed	3+ Lanes Closed	Total
Mean percent of incidents	75.4%	19.6%	3.1%	1.9%	100.0%
Mean duration (min)	34.0	34.0	53.6	69.6	35.4*

Note: *Average weighted by the relative frequencies.

Finally, the probability of an incident type is computed as follows:

$$PT(t, m) = 1 - e^{-(I(m) \times P(i) \times t_E(i) / t_{SP})}$$

where

$PT(t, m)$ = Probability that incident type t is present in month m ,

$I(m)$ = Expected number of incidents in subject direction in month m ,

$P(i)$ = Proportion of incidents of type i ,

$t_E(i)$ = Mean event duration of incidents of type i (min), and

t_{SP} = Study period duration (min).

The resulting estimated average percent time with incidents present on the facility is shown in Exhibit 37-39 (results specific to individual demand patterns are too numerous to show here).

Month	Incident Type					
	No Incident	Shoulder Closed	1 Lane Closed	2 Lanes Closed	3 Lanes Closed	4 Lanes Closed
January	66.42%	23.30%	7.06%	1.79%	1.43%	0.00%
February	66.36%	23.34%	7.08%	1.79%	1.43%	0.00%
March	65.10%	24.18%	7.36%	1.87%	1.49%	0.00%
April	63.79%	25.05%	7.66%	1.94%	1.56%	0.00%
May	63.87%	25.00%	7.64%	1.94%	1.55%	0.00%
June	64.53%	24.56%	7.49%	1.90%	1.52%	0.00%
July	64.10%	24.85%	7.59%	1.93%	1.54%	0.00%
August	65.30%	24.04%	7.32%	1.86%	1.48%	0.00%
September	65.97%	23.60%	7.17%	1.82%	1.45%	0.00%
October	65.04%	24.22%	7.38%	1.87%	1.50%	0.00%
November	66.79%	23.05%	6.98%	1.77%	1.41%	0.00%
December	68.56%	21.86%	6.59%	1.67%	1.33%	0.00%

The entries in Exhibit 37-39 represent the probability of having a given incident type in each month. The values were computed using a crash rate of 164.5 per 100 million VMT, a rounded crash-to-incident expansion factor of 7, and a seed VMT of 330,006 in Equation 37-78. Incidents were computed using Equation 37-77. Monthly and annual values total to 100% for each demand pattern.

Exhibit 37-38

Example Problem 1: Mean Duration and Distribution of Incidents by Severity

Equation 37-78

Exhibit 37-39

Example Problem 1: Estimated Percent Time Incidents Present on I-40 Eastbound

*Step 6: Scenario Generation**Initial Scenario Development*

The initial scenario represents a specific combination of a demand level, a weather type, and an incident type. The demand levels are specified by month and day of week rather than by volume level. This enables the analyst to partially account for the effects of demand on incidents, and the effects of weather on demand, by using calendar-specific weather and incident probabilities.

The initial estimate of the percent time that each scenario represents of the reliability reporting period is the product of the demand, weather, and incident type percent times that combine to describe the scenario. The assumption is that the percent time of incidents and the percent time of weather are a function of the calendar month and that other correlations between demand, incidents, and weather can be neglected.

Equation 37-79

$$PT(d, w, i) = PT(d) \times PT(w|d) \times PT(i|d)$$

where

$PT(d, w, i)$ = Percent time associated with demand pattern d with weather type w and incident type i ,

$PT(d)$ = Percent time of demand pattern d within the reliability reporting period,

$PT(w|d)$ = Percent time of weather type w associated with demand pattern d ,

$PT(i|d)$ = Percent time of incident type i associated with demand pattern d .

Exhibit 37-40 shows the initial estimated scenario percent times before the details as to starting time, location, and duration of incidents and weather have been specified. This table shows the results for only normal weather conditions. Similar computations and results are obtained for the other weather conditions. *Note that the initial probabilities for all weather and incident conditions must sum to the percent time for each demand pattern within each season.*

For computing percent time of incident type i associated with demand pattern d , the probabilities presented in Exhibit 37-40 are averaged and weighted by the number of days each demand pattern has in the calendar.

Exhibit 37-40
Example Problem 1: Percent Times for Incident Scenarios in Non-severe Weather

Season	Day	No Incident	Shoulder Closure	1 Lane Closed	2 Lanes Closed	3 Lanes Closed	Subtotal Non-Severe Weather	Subtotal Severe Weather	Total
Winter	M-W	8.847%	3.005%	0.909%	0.230%	0.184%	13.176%	1.000%	14.176%
	Thu	3.110%	1.053%	0.319%	0.081%	0.064%	4.626%	0.355%	4.981%
	Fri	3.344%	1.135%	0.343%	0.087%	0.070%	4.979%	0.385%	5.364%
Spring	M-W	9.660%	3.710%	1.132%	0.287%	0.230%	15.019%	0.307%	15.326%
	Thu	3.139%	1.210%	0.369%	0.094%	0.075%	4.887%	0.094%	4.981%
	Fri	3.139%	1.210%	0.369%	0.094%	0.075%	4.887%	0.094%	4.981%
Summer	M-W	9.848%	3.724%	1.135%	0.288%	0.230%	15.226%	0.100%	15.326%
	Thu	3.196%	1.212%	0.370%	0.094%	0.075%	4.946%	0.035%	4.981%
	Fri	3.196%	1.212%	0.370%	0.094%	0.075%	4.946%	0.035%	4.981%
Fall	M-W	9.702%	3.468%	1.053%	0.267%	0.213%	14.704%	0.239%	14.943%
	Thu	3.224%	1.155%	0.351%	0.089%	0.071%	4.889%	0.092%	4.981%
	Fri	3.232%	1.161%	0.353%	0.089%	0.072%	4.907%	0.074%	4.981%
Total	All	63.637%	23.255%	7.073%	1.794%	1.434%	97.194%	2.806%	100.000%

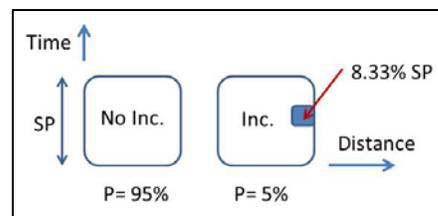
All entries are percent time within the reliability reporting period when the specified conditions are present on facility. Not shown are percentages for rain, snow, and low visibility conditions. Percentages are computed using Equation 37-79 and percentages from Exhibit 37-35, Exhibit 37-37, and Exhibit 37-39.

Study Period Scenario Development

The estimated percent times for each condition must be converted to scenario probabilities so that scenario performance results can be appropriately weighted when computing overall travel time reliability.

Each inclement weather scenario (rain, snow, etc.) and each incident scenario involving a shoulder or lane closure does not persist for the entire duration of the study period. Therefore, the probabilities of each of these scenarios must be weighted to ensure that these scenarios sum to the appropriate total percentage times predicted for each of these events.

As an example to illustrate the concept, consider a single non-recurrent congestion event—say the occurrence of an incident. Incident logs obtained from the responsible state agency indicate that during the study period (say 6 h) for all weekdays in a year the probability of an incident was 5%. This situation would be modeled as two separate initial scenarios each 6 h long; one without an incident with an assigned 95% probability, and the other with an incident with 5% probability. We do not (and definitely should not) model a continuous 6-h incident as a full scenario. This is where the initial scenario definition ends. In order to actually model the effect of a scenario, additional details are needed, such as the duration of the incident. If the incident lasted for 30 min, the overall incident probability inside the incident study period would be computed as $(0.5 \text{ h}) / (6 \text{ h}) = 8.33\%$. The two initial scenarios and probabilities are illustrated in Exhibit 37-41.



Note: Inc. = incident.

This modeling scheme clearly results in a bias in the analysis, since much of the initial scenario with the incident actually contains many time periods where there are no incidents. This is important since all probabilities are computed time-wise. In fact, if one accepts the above definitions, the resulting probability of an incident would actually be $= 0.0833 \times 0.05 = 0.416\%$, which is much less than the actual 5% incident probability observed on the facility. Similarly, the probability of a non-incident would be 99.58%, not 95%. These are crucial differences in probabilities that will have a significant impact on the resulting travel time distribution. The differences between the stated probability and its correct value also increase when the number of scenarios (inevitably) increases.

Exhibit 37-41
Example Problem 1:
Schematic of Two Initial
Scenarios and Probabilities

The simplest approach to overcome these differences is to readjust the relevant initial scenario probabilities such that the original incident probability is honored in all cases. This can be done using a simple equation to estimate the true study period scenario probability Π from Equation 37-80.

Equation 37-80

$$\Pi = P \times \frac{\text{SP duration (min)}}{\text{Event duration (min)}}$$

The probability $\Pi = 0.05 \times (6 \times 60) / 30 = 0.60$, or 60% for the study period incident scenario, and by the rule of complementary probability, 40% for the non-incident scenario, a rather large swing from the initial probabilities. In fact, the algorithm results in lowering the probability of no-event scenarios and transferring those probabilities to the event-based scenarios. The overall probability of an incident is now $0.60 \times 0.0833 = 5\%$, which was the originally stipulated incident probability.

An interesting twist occurs if the average event duration is too short (or the study period duration excessively long). In the example above, if the incident duration was 15 min, Equation 37-80 would yield an adjusted probability of 1.2. This implies that there is an incompatibility between the stated probability and the average incident duration. In this case, the duration must be adjusted upward in intervals of 15 min (corresponding to analysis period lengths), until the probability drops below 1. In this example, the next interval would be a 30-min incident, with the probabilities as computed in the previous paragraph.

Exhibit 37-42 shows the final estimated study period scenario probabilities for the scenarios involving non-severe weather. Not shown are similar tables for rain, snow, and low visibility conditions used to derive the severe weather column.

Exhibit 37-42
Example Problem 1:
Estimated Incident Study
Period Scenario Probabilities
after Adjustment

Season	Day	Non-Severe Weather					Weather Subtotals		Total
		No Incident	Shoulder Closed	1 Lane Closed	2 Lanes Closed	3 Lanes Closed	Non-Severe	Severe	
Winter	M-W	0.008%	4.006%	3.637%	1.373%	0.871%	9.896%	4.28%	14.176%
	Thu	0.027%	1.404%	1.274%	0.481%	0.305%	3.491%	1.49%	4.981%
	Fri	0.018%	1.513%	1.374%	0.519%	0.329%	3.753%	1.61%	5.364%
Spring	M-W	0.431%	4.947%	4.529%	1.706%	1.083%	12.695%	2.63%	15.326%
	Thu	0.153%	1.614%	1.478%	0.557%	0.354%	4.155%	0.83%	4.981%
	Fri	0.153%	1.614%	1.478%	0.557%	0.354%	4.155%	0.83%	4.981%
Summer	M-W	0.581%	6.384%	4.541%	1.721%	1.098%	14.324%	1.00%	15.326%
	Thu	0.161%	2.078%	1.478%	0.560%	0.357%	4.634%	0.35%	4.981%
	Fri	0.161%	2.078%	1.478%	0.560%	0.357%	4.634%	0.35%	4.981%
Fall	M-W	0.167%	5.946%	4.213%	1.591%	1.012%	12.929%	2.01%	14.943%
	Thu	0.206%	1.732%	1.403%	0.529%	0.336%	4.206%	0.78%	4.981%
	Fri	0.087%	1.991%	1.411%	0.533%	0.339%	4.361%	0.62%	4.981%
Total	All	2.154%	35.305%	28.293%	10.687%	6.795%	83.235%	16.77%	100.00%

Notes: M = Monday, W = Wednesday, Thu = Thursday, and Fri = Friday.

Operational Scenario Development

The incident starting time, duration, and location must be specified for incident scenarios. To ensure that a representative cross-section of performance results are obtained, each incident study period scenario involving a closure of some kind is subdivided into 18 possible operational scenarios (2 start times, 3 locations, and 3 durations):

- Start at the beginning or the middle of the study period;
- Located at the beginning, middle, or end of the facility; and
- Occurring for the 25th, 50th, or 75th percentile highest duration for a given incident type.

Note that some operational scenario options may be prohibited. For example, if the beginning, middle, or end of the facility only has 3 lanes, then the 3-lane closure scenario is not modeled for this condition. In this case, the operational scenario is removed from the total list of operational scenarios and its probability is assigned proportionally to the remaining operational scenarios.

Each of the 18 incident operational scenarios is considered equally probable within the study period scenario. Thus each operational scenario is given 1/18th the probability of the study period scenario for the incident type.

For example, the study period scenario associated with demand pattern 1 (Monday–Wednesday in winter), with non-severe weather, and a shoulder closure has a 4.00645% probability of occurrence. Then, the operational scenario associated with the incident starting at the beginning of the study period, in the middle segment, and for an average duration will have a $4.00645\% / 18 = 0.22258\%$ probability of occurrence.

The starting time and duration must also be specified for the severe weather scenarios (rain, snow, etc.). Weather is assumed to apply equally across the entire facility. To ensure that a representative cross-section of performance results is obtained, each severe weather study period scenario is subdivided into two possible operational scenarios:

- Severe weather beginning at the start of the study period, and
- Severe weather beginning in the middle of the study period.

Each weather operational scenario for each severe weather study period scenario is given one-half the probability of the study period scenario for the weather type.

For example, the study period scenario associated with demand pattern 1 (Monday–Wednesday in winter), with light snow weather, and no incident has a 0.22294% probability of occurrence. Therefore, the operational scenario associated with the weather event starting at the beginning of the study period will have a $0.22294\% / 2 = 0.11147\%$ probability of occurrence.

Removal of Improbable and Infeasible Scenarios

Theoretically, the procedure can generate up to 22,932 operational scenarios for the subject facility. Many of these may have exceptionally low or near-zero probability. In addition, some may be infeasible—for example, a 2- or 3-lane closure on a 2-lane freeway segment. For this example, the improbable and zero-probability operational scenarios were removed from the reliability analysis. This translates to an inclusion threshold of near “zero” meaning that all scenarios with probability greater than zero are included in the analysis. This leaves 2,058 scenarios to be used in evaluating travel time reliability for the I-40 facility, as shown in Exhibit 37-43

Exhibit 37-43

Example Problem 1: Final Scenario Categorization

Scenario Type	Number of Operational	
	Scenarios	Percent of Total
No incidents and non-severe weather	12	0.6%
No incidents and severe weather	66	3.2%
Incidents and non-severe weather	528	25.7%
Incidents and severe weather	1452	70.6%
Total	2,058	100.0%

It should be noted that the percentages shown here are *not the probabilities of occurrence*. They indicate the proportionate number of HCM analyses that will be performed on each scenario type for the reliability analysis. This is because each 6-h study period for incident and weather scenarios contains many 15-min analysis time periods characterized by fair weather and no incident conditions. The numbers shown in Exhibit 37-43 assure that the initial incident and weather probabilities are honored.

Step 7: Apply the HCM 2010 Analysis Method

The HCM 2010 freeway facility analysis method is applied to each of the 2,058 operational scenarios with capacity and speed-flow curve adjustments appropriate for each scenario.

The standard HCM freeway speed-flow curves are not appropriate when modeling incidents and weather. Therefore, as described in Chapter 37, a modified version of Equation 25-1 from Chapter 25, Freeway Facilities: Supplemental, is used in combination with the combined CAFs and SAFs to predict basic freeway segment performance under incident and severe weather scenarios:

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

where

S = segment speed (mi/h),

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

SAF = segment speed adjustment factor,

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

CAF = capacity adjustment factor, and

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

Capacity adjustment and free-flow speed adjustment factors for weather are selected for the I-40 facility based on its free-flow speed of 70 mi/h, as shown in Exhibit 37-44:

	Medium Rain	Heavy Rain	Light Snow	Light-Medium Snow	Low Visibility	Non-severe Weather
CAF	0.91	0.84	0.95	0.90	0.90	1.00
SAF	0.93	0.92	0.87	0.86	0.94	1.00

The CAFs for segments with incidents on I-40 are selected based on the number of lanes in the subject direction for the segment where the incident is located (Exhibit 37-45). The free-flow SAF for incidents is set at 1.00. It is

Exhibit 37-44

Example Problem 1: Free-flow CAFs and SAFs for Weather on I-40

important to note that the factors in Exhibit 37-45 do not include the effect of the number of closed lanes. In other words, both the number of lanes closed and the resulting capacity per open lane on the segment must be specified by the user.

Directional Lanes	No Incident	Shoulder Closure	1 Lane Closed	2 Lanes Closed	3 Lanes Closed
2	1.00	0.81	0.70	N/A	N/A
3	1.00	0.83	0.74	0.51	N/A
4	1.00	0.85	0.77	0.50	0.52

Note: N/A = scenario not feasible.

For scenarios with both incidents and severe weather, the CAFs are multiplied to estimate their combined effect. CAFs and SAFs are also applied to the merge, diverge, and weaving segments along the facility.

Step 8: Quality Control and Error Checking, and Inclusion Thresholds

Quality control and error checking starts with the base scenario (seed file) and proceeds to the non-incident, non-severe weather scenarios.

Error Checks of the Seed File

It is difficult to quality control 2,058 scenarios, so it is recommended that the analyst focus on error checking and quality control on the single initial HCM seed file that is used to generate the 2,058 scenarios. The file should be error checked to the analyst's satisfaction to ensure that it accurately represents real world congestion on the freeway facility under recurring demand conditions with no incidents and under non-severe 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 seed file will be crucial, because it will be multiplied 2,058 times by the scenario generator.

Error Checks for Non-Incident and Non-severe Weather Scenarios

Once the seed file has been error checked, the next step is to look at the denied entry statistic for each of the scenarios that do not involve severe weather or incidents. The number of vehicles denied entry to the facility (and not stored on one of its entry links or ramps) should be as near zero as possible for non-severe weather, non-incident conditions. If feasible, the entry links and ramps should be extended in length to ensure that all vehicle delays for these *demand-only* scenarios are accounted for within the facility or its entry links and ramps.

The number of vehicles queued on the facility (and its entry links and ramps) during the first analysis period should be nearly the same as the number of vehicles queued in the last analysis period. If necessary, the study period should be extended with one or more artificial analysis periods to ensure that there is not a great change in the number of vehicles queued within the facility between the beginning and the end of the study period. Ideally, the number of vehicles queued in the first and last analysis periods should be zero.

Exhibit 37-45

Example Problem 1: CAFs per Open Lane for Incidents on I-40

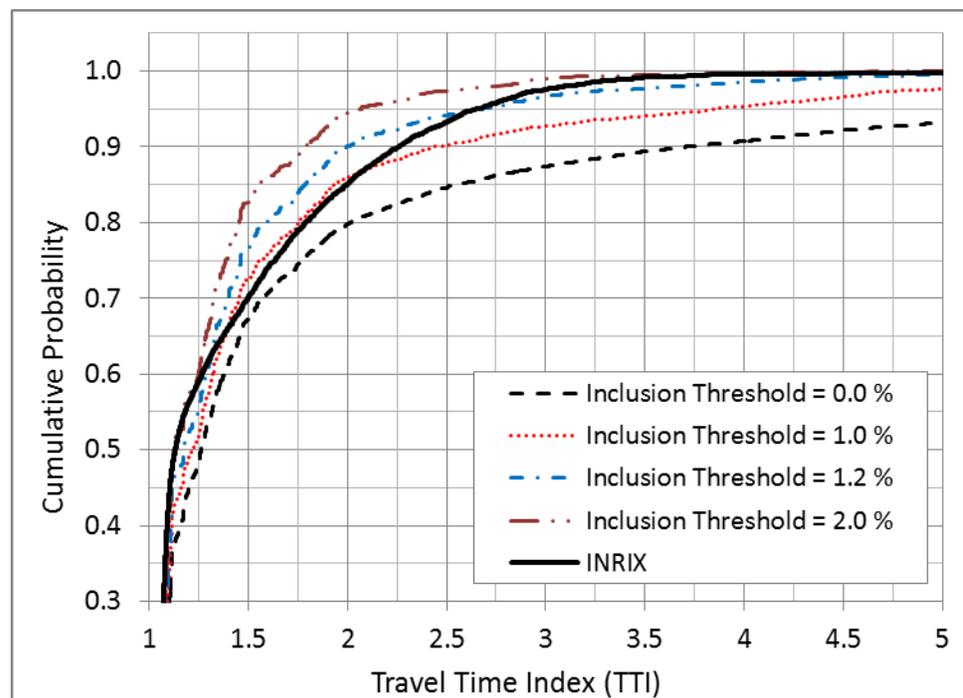
Inclusion Thresholds

As mentioned earlier, the procedure can generate several thousand scenarios many of which may have exceptionally low or exactly zero probability. In addition, some scenarios may be infeasible. The infeasible scenarios are automatically filtered out by the freeway scenario generation procedure. The scenarios with extremely low probability are not expected to be observed in the field in a single year; however, they are included in the predicted TTI distribution (with an inclusion threshold of zero). This makes the comparison of the predicted and observed distributions hard to interpret. In addition, these scenarios tend to have exceptionally large TTI values that significantly shift the tail of the cumulative distribution to the right (i.e., towards higher TTI values). These scenarios may also result in demand shifts in the real world that are not directly accounted for in the freeway reliability method.

As such, the procedure allows the user to specify an “inclusion threshold” to only include scenarios with probability larger than the threshold specified in the analysis. For instance, an inclusion threshold of “1.0%” means that only the scenarios with probability larger than 0.01 are considered in the analysis. Exhibit 37-46 presents the TTI cumulative distributions for four different inclusion threshold values for the subject facility as well as the observed TTI distribution obtained from a probe data warehouse. For the subject facility, including all the scenarios with a non-zero probability in the analysis (i.e., inclusion threshold = zero) resulted in a general overestimation in the TTI cumulative distribution. Increasing the threshold to 1.0% brought the TTI distribution much closer to the observed distribution. An inclusion threshold of 1.2% resulted in generally matching PTI values for the predicted and observed TTI distributions. Inclusion thresholds larger than 1.2% yielded a general underestimation in the TTI distribution.

Exhibit 37-46

Example Problem 1: Travel Time Distribution Results for Different Inclusion Thresholds



Increasing the value of the inclusion threshold reduces the number of scenarios and consequently the runtime; however, at the same time it reduces the percentage of the coverage of feasible scenarios (Exhibit 37-47). In other words, the larger the value of the inclusion threshold, the higher the number of scenarios excluded from the analysis. As such, fewer numbers of feasible scenarios are covered.

Inclusion Threshold	Number of Scenarios	Percent Coverage of the Distribution
0.00%	2,058	100.00
0.01%	1,004	99.71
0.10%	496	97.46
1.00%	264	89.63
1.20%	210	85.07
1.30%	174	82.55
2.00%	84	75.91
3.00%	81	67.04
4.00%	4	37.32

As shown in Exhibit 37-47, the number of scenarios significantly drops as the value of the inclusion threshold is increased. Going from an inclusion threshold of 0.00% to 0.01% eliminated half of the scenarios and decreased the coverage of the distribution by only 0.29%. This means that more than 1,000 of the scenarios contributed to only 0.29% of the TTI distribution.

Step 9: Interpreting Results

This step compares the reliability results to the agency's established thresholds of acceptability and the diagnoses of the major contributors to unreliable travel times on I-40. The core and supplemental reliability performance measures computed for the example problem are shown in Exhibit 37-48. It should be noted that each observation from the I-40 data represents a 15-min mean TTI. For example, the PTI value of 5.34 is interpreted as the TTI associated with the highest 5th percentile analysis period out of *all* analysis periods covered in the reliability reporting period (in this case, $2,058 \times 24 = 49,392$ periods). It is critical that when certain TTI parameters are compared to each other, that they are computed for identical time periods.

Measure	Value
Mean TTI	1.97
PTI	5.34
80th percentile TTI	2.03
Semi-standard deviation	2.41
Failure/On-Time (40 mi/h)	0.26
Standard deviation	2.21
Misery index	9.39
Reliability Rating	54.0%

The PTI was computed by finding the 95th percentile highest analysis period average facility TTI for the subject direction of travel. The 80th percentile TTI was simply the 80th percentile highest TTI (each of which is the average TTI for the analysis period for that scenario).

The semi-standard deviation was computed by subtracting 1 (in essence, the TTI at free-flow speed) from each of the facility average TTIs for each of the

Exhibit 37-47

Example Problem 1: Number of Scenarios and Coverage of Feasible Scenarios

Exhibit 37-48

Example Problem 1: Reliability Performance Measure Results for I-40

analysis periods, squaring each result, weighting each result by its probability, and summing the results. The square root of the summed results was then taken to obtain the semi-standard deviation.

$$SSD = \sqrt{\sum_s P_s (TTI_s - 1)^2}$$

where

SSD = semi-standard deviation (unitless),

P_s = probability for analysis period s , and

TTI_s = facility average travel time index for analysis period s (unitless).

The failure/on-time index was computed by summing the probability of all analysis periods that have an average speed less than 40 mi/h:

$$FOTI = \sum_{s \in S_{40}} P_s$$

where

$FOTI$ = failure/on-time index (unitless), and

S_{40} = a set including all analysis periods with average speeds less than 40 mi/h.

The standard deviation was computed by subtracting the average analysis period TTI (over the reliability reporting period) from each of the facility average TTIs for each of the analysis periods, squaring each of the results, weighting each result by its probability, and summing the results. The square root of the summed results was then taken to obtain the standard deviation.

$$SD = \sqrt{\sum_s P_s (TTI_s - \overline{TTI})^2}$$

where

SD = standard deviation (unitless), and

\overline{TTI} = average analysis period TTI over the reliability reporting period.

The misery index was computed by averaging the highest 5% of travel times divided by the free-flow travel time, or in other words, by averaging the highest 5% TTIs.

$$MI = \frac{\sum_{s \in T_5} P_s TTI_s}{\sum_{s \in T_5} P_s}$$

where

MI = misery index (unitless), and

T_5 = a set including highest top 5% TTIs.

During the scoping process for this example, the agency selected the mean TTI and the PTI as its reliability performance measures for this study. The calculated TTI and the PTI are compared to the thresholds of acceptable performance established at the start of this example problem (Exhibit 37-49). Both statistics fall above the 90th percentile among freeways in weekday a.m.

peak period in the SHRP 2 L08 dataset, and consequently do not meet the agency's threshold of acceptability for reliable performance.

Statistic	I-40 Reliability	Agency Threshold of Acceptability	Conclusion
Mean TTI	1.97	< 1.93	Marginally Unsatisfactory
PTI	5.34	< 3.55	Unsatisfactory

The agency's congestion management goal is to operate its freeways at better than 40 mi/h during 50% of the peak periods of the year and better than 25 mi/h during 95% of the peak periods during the year. The TTI shown in Exhibit 37-49 is recomputed for 40 mi/h and is found to be 1.13 (Exhibit 37-50). This value is larger than 1.00, which means that the agency has not achieved this congestion management goal for the I-40 freeway. Similarly, the PTI shown in Exhibit 37-49 is recomputed for 25 mi/h and found to be less than or equal to 1.00, meaning that this goal was achieved.

Statistic	I-40 Reliability (at 70 mi/h)	I-40 Reliability (at 40 mi/h)	I-40 Reliability (at 25 mi/h)	Agency Threshold of Acceptability	Conclusion
Policy Index	1.97	1.13	0.68	> 1.00	Unsatisfactory

Remarks

As noted in the "Inclusion Threshold" section, a comparison of the TTI estimated using this chapter's travel time variability methodology to the TTI obtained from probe data for the subject facility found that TTI was generally overestimated when all scenarios were included in the analysis. This is because (a) the methodology does not automatically adjust demand to reflect shifts in demand when rare, but severe, incidents or weather conditions occur, and (b) not all of the rare events accounted for in the HCM method may occur in a given year of field data. Excluding the rarest 1.2% of scenarios resulted in a much better agreement between the HCM results and one year field measurements for this particular facility (different inclusion thresholds may produce the best agreement on other facilities).

Therefore analysts should keep in mind that using direct sources of TTI data may yield different results or a different conclusion. Analysts should also keep in mind that even though a lower TTI or PTI than predicted by the HCM method may be observed on a given facility as a result of demand-shifting, the field-measured values do not necessarily reflect the longer travel times experienced by the drivers who take other routes or incur the inconvenience of making their trips at a different time than desired.

Exhibit 37-49

Example Problem 1:
Evaluation of TTI and PTI
Results for I-40

Exhibit 37-50

Example Problem 1:
Evaluation of Policy TTI and
PTI Results for I-40

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

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