CHAPTER 7
INTERPRETING HCM AND ALTERNATIVE TOOL RESULTS

CONTENTS

LIST OF EXHIBITS

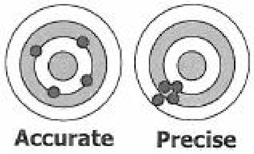
1. INTRODUCTION

OVERVIEW

The ever-increasing variety of tools provided by the evolution of computer software makes the conduct of transportation analyses that take into account a wide variety of factors easy. However, the analyst still needs to have a full understanding of the methodologies used by the selected analysis tools—including the level of uncertainty in the tools' results—to make well-informed recommendations based on the analysis results and to communicate those results to others. As tools become more complex, the analyst's challenge increases.

Uncertainty, variability, accuracy, and precision are related concepts that need to be considered when model results are interpreted and presented.

Highway Capacity Manual (HCM) methods—like any other analysis tool—produce performance measure results that are estimates of the true value of a measure. These results are subject to *uncertainty* that derives from (*a*) uncertainty in a model's inputs; (*b*) uncertainty in the performance measure estimate produced by a model; and (*c*) imperfect model specification, in which a model may not fully account for all the factors that influence its output. Uncertainty in model inputs, in turn, can result from (*a*) the *variability* of field-measured values, (*b*) the uncertainty inherent in forecasts of future volumes, and (*c*) the use of default values.



The *accuracy* of a model's results is directly related to its uncertainty. Models that incorporate more factors may appear to be more accurate, but if the inputs relating to the added factors are highly uncertain, accuracy may actually be decreased. Analysts should also carefully consider the *precision* used in presenting model results to avoid implying more accuracy than is warranted.

Alternative tools often provide performance measures that have names the same as or similar to HCM measures but that are defined differently.

Finally, when both HCM-based and alternative tools are used in an analysis, or when a performance measure produced by an alternative tool is used to determine level of service (LOS), it is important to ensure that the alternative tool's measures are defined in the same way as the HCM measures. Alternative tools use different definitions for similarly named measures, which may lead to inaccurate conclusions if the differences are not accounted for properly.

CHAPTER ORGANIZATION

Section 2 covers the concepts of uncertainty, variability, accuracy, and precision. It discusses sources of uncertainty and methods for addressing variability during an analysis and provides guidance on the level of precision to use during an analysis and in presenting analysis results.

Section 3 describes the primary performance measures produced by HCM methods, explores the use of vehicle trajectory analysis to define and estimate consistent performance measures for basic automobile flow parameters, contrasts the HCM's deterministic (i.e., nonvarying) analysis results with the stochastic (i.e., randomly varying) results from simulation tools, and provides guidance on comparing HCM analysis results with results from alternative tools.

RELATED HCM CONTENT

Other HCM content related to this chapter is the following:

- Chapter 4, Traffic Operations and Capacity Concepts, in which Section 2 introduces basic automobile flow parameters, including speed, delay, density, number of stops, and travel time reliability, and introduces the concept of vehicle trajectory analysis as the lowest common denominator for estimating these basic parameters;
- Chapter 6, HCM and Alternative Analysis Tools, which describes the range of tools available for analyzing transportation system performance;
- Chapter 36, Concepts: Supplemental, in which Section 2 provides guidance on presenting analysis results to facilitate their interpretation by others, Section 4 provides selected reliability data from U.S. roadways to help analysts interpret travel time reliability analysis results, and Section 5 provides detailed guidance on using vehicle trajectory analysis for comparing performance measures from different analysis tools;
- The Example Results subsections within the Applications sections of Volume 2 and 3 chapters, which graph the sensitivity of service measure results to variations in input parameter values;
- The Use of Alternative Tools subsections within the Applications sections of all Volume 2 and 3 chapters, which provide specific guidance on developing HCM-compatible performance measures from alternative tools and highlight conceptual modeling differences that may preclude direct comparisons of HCM and alternative tool results;
- Case Study 6, I-465 Corridor, Indianapolis, in the *HCM Applications Guide* in Volume 4, which demonstrates the interpretation of simulation tool results; and
- The *Planning and Preliminary Engineering Applications Guide to the HCM* in Volume 4, which provides guidance on and case study examples of applying the HCM in conjunction with transportation planning models.

2. UNCERTAINTY AND VARIABILITY

UNCERTAINTY AND VARIABILITY CONCEPTS

Model outputs—whether from the HCM or alternative tools—are estimates of the "true" values that would be observed in the field. Actual values will lie within some range of the estimated value.

The performance measure results produced by traffic models—both HCM based and alternative tools—are estimates of the "true" values that would be observed in the field. These estimates are not exact, however—they are subject to statistical uncertainty, and the true value of a given measure lies within some range of the estimated value.

Sources of variability in correctly measured values used as model inputs. Measurement error is yet another form of uncertainty.

To illustrate the lack of exactness, consider the *variability* in measured values, such as traffic volume inputs. There are several types of variability:

- *Temporal variability*, in which measured values, such as hourly traffic volumes, vary from day to day or month to month at a given location;
- *Spatial variability*, in which measured values, such as the percentage of trucks in the traffic stream, vary from one location to another within a state or from one state to another; and
- *User perception variability*, in which different users experiencing identical conditions may perceive those conditions differently—for example, when they are asked to rate their satisfaction with those conditions.

Sources of uncertainty in model outputs.

Chapter 5, Quality and Level-of-Service Concepts, noted that model outputs are subject to three main sources of *uncertainty* (*1*):

1. Uncertainty in model inputs, such as variability in measured values, measurement error, uncertainty inherent in future volume forecasts, and uncertainty arising from the use of default values;
2. The uncertainty of the performance measure estimate produced by a model, which in turn may rely on the output of another model that has its own uncertainty; and
3. Imperfect model specification—a model may not fully account for all the factors that influence the model output.

Uncertainty cannot be eliminated, but its effects can be reduced through a variety of techniques.

Although uncertainty cannot be eliminated, its effects can be reduced to some extent. For example, the LOS concept helps to dampen the effects of uncertainty by presenting a range of service measure results as being reasonably equivalent from a traveler's point of view. The use of a design hour, such as the 30th-highest hour of the year, also reduces uncertainty, since the variability of the design hour motorized vehicle volume is much lower than the variability of individual hourly volumes throughout the year (*1*). Measures of travel time reliability quantify the extent to which travel time varies on a facility.

Measured values will have more certainty than default values, and multiple observations of a model input will provide more certainty than a single observation. Performance measures describing the distribution of measured or estimated values help portray the range of variability of the values. Finally, sensitivity analyses—described later in this section—and other statistical techniques (*2*) can be used to test the impact of changes in model inputs on model outputs.

SOURCES OF UNCERTAINTY

Input Variables

HCM procedures and alternative tools typically require a variety of input data. Depending on the situation, an analyst can provide these inputs in up to three ways. In order of increasing uncertainty, they are (*a*) direct measurement, (*b*) locally generated default values, and (*c*) national default values suggested by the HCM or built into an alternative tool. Default values may not reflect spatial and temporal variability—national defaults to a greater extent than local defaults—because the mix of users and vehicles varies by facility and by time of day and because drivers' behavior depends on their familiarity with a facility and prevailing conditions. Direct measurements are subject only to temporal variability, since the measurement location's site-specific differences will be reflected in the observed values.

Traffic volume variability from day to day and unknowns associated with future-year traffic volume forecasts are among the primary sources of uncertainty.

Day-to-day variability in traffic volume is a primary source of uncertainty in traffic analyses (*1, 3*). Unknowns concerning development patterns and timing, the timing of changes or additions to other parts of the transportation system, and changes in use of particular travel modes cause longer-range forecasts to be subject to higher degrees of uncertainty than shorter-range forecasts. Other input variables whose uncertainty has been studied in the literature are saturation flow rates, critical headways, follow-up time, and driver behavior (*4, 5*).

Model Accuracy and Precision

Model Development

Many HCM models are based on theoretically derived relationships, which include assumptions and contain parameters that must be calibrated on the basis of field data. Other HCM models are primarily statistical. The accuracy and precision of these models can be described in terms of standard deviations, coefficients of determination of linear regression (R^2), and other statistical measures.

Documentation of the uncertainty inherent in HCM models can be found in the models' original research reports, many of which are located in the Technical Reference Library in Volume 4.

Only some of the older HCM models (i.e., those first appearing in the HCM2000 or earlier editions) have well-documented measures of uncertainty. On occasion, the Transportation Research Board's Committee on Highway Capacity and Quality of Service has exercised its judgment in modifying models to address illogical results (e.g., at boundary conditions) or to fill in gaps in small databases. In such cases, the "true" uncertainty of the entire model is virtually impossible to quantify. In contrast, most models developed for the HCM 2010 have documented measures of uncertainty. This information is provided in the original research reports for the HCM methodologies, which can be found in the Technical Reference Library in Volume 4.

Nested Algorithms

In many methodologies, the algorithm used to predict the final service measure relies on the output of another algorithm, which has its own uncertainty. Thus, the uncertainty of the final algorithm is compounded by the uncertainty in an input value derived from another algorithm.

In Chapter 13, Freeway Weaving Segments, for example, the prediction of weaving and nonweaving speeds depends on the free-flow speed and the total number of lane changes made by weaving and nonweaving vehicles. Each of these inputs is a prediction based on other algorithms, each having its own uncertainty. Other examples are the urban street facility and freeway facility procedures, which are built on the results of underlying segment and (for urban streets) point models, the outputs of which have their own associated uncertainties.

Traveler Perception

Different people will have different levels of satisfaction with identical conditions.

The HCM 2010 introduced several traveler perception–based models for estimating LOS for the bicycle, pedestrian, and transit modes. In addition, Chapter 18, Urban Street Segments, provides an alternative traveler perception model for the automobile mode to help support multimodal analyses. These models produce estimates of the average LOS travelers would state for a particular system element and mode. However, people perceive conditions differently, which results in a range of responses (often covering the full LOS A to F range) for a given situation. As with other models, statistical measures can be used to describe the variation in the responses as well as the most likely response (*6*).

Additional Documentation

In addition to the uncertainty values given in the original research for HCM methods, the uncertainty of a number of current HCM models has been studied in the literature. These studies include unsignalized intersections (*5, 7, 8*), two-lane highways (*9*), and other uninterrupted-flow facilities (*10*).

Model Specification

A final potential source of uncertainty is an incomplete model specification, in which not all the factors that influence a model's result are reflected in the model's parameters. (An inaccurate specification, in which the wrong parameters are included in the model, also falls into this category.)

A more complex model is not necessarily a more accurate model.

However, a diminishing-returns principle applies to model complexity. Each new variable added to a model brings with it uncertainty related both to the model's parameters and to its input values. The additional complexity may not be warranted if the model's final output becomes more uncertain than before, even if the model appears to be more accurate because it takes additional factors into account. Model complexity that leads to better decision making is justified; complexity that does not is best avoided (*11*).

SENSITIVITY ANALYSIS

One way to address the uncertainty inherent in a performance measurement estimate is to conduct a sensitivity analysis, in which key model inputs are individually varied over a range of reasonable values and the change in model outputs is observed. A good understanding of the sensitivity of model inputs is important, and special care should be taken in selecting appropriate values for particularly sensitive parameters. Analysts and decision makers also need to understand the sensitivity of model outputs (numerical values or the LOS letter grade) to changes in inputs, particularly volume forecasts, when they interpret the results of an analysis.

Sensitivity analysis is a useful technique for exploring how model outputs change in response to changes in model inputs.

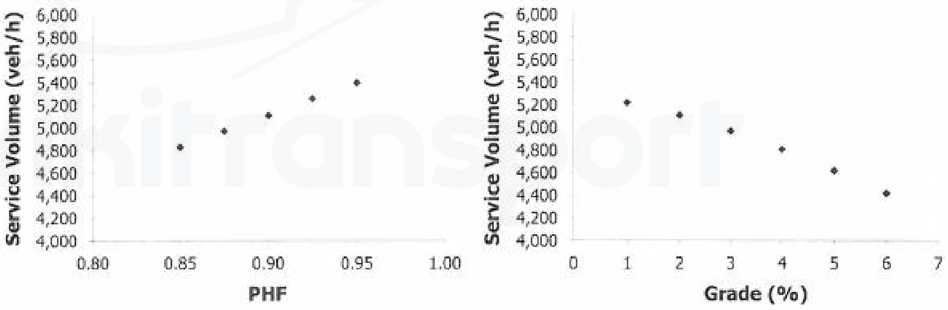
Exhibit 7-1 illustrates a sensitivity analysis for selected inputs to the basic freeway segment method. A typical application would be a planning study for a future freeway, where not all the inputs are known exactly. The output being tested is the service volume (in vehicles per hour, veh/h) for LOS D (i.e., the highest volume that results in LOS D, given the other model inputs). The following inputs were held constant in all three examples:

- Base free-flow speed: 75 mi/h
- Lane width: 12 ft
- Percent trucks: 5% (30% single-unit, 70% tractor-trailer)
- Speed and capacity adjustment factors (e.g., weather): 1.00
- Number of lanes per direction: 3
- Shoulder width: 6 ft
- Grade length: 1 mi

In each example, one of the following inputs was varied, while the other two were held constant. The varied input differs in each example:

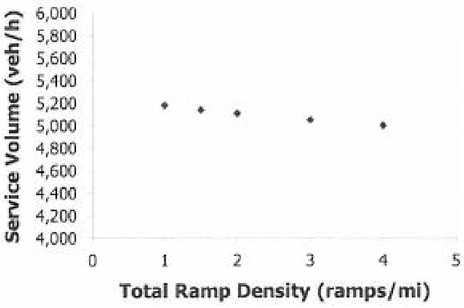
- Peak hour factor (PHF): 0.90, varied from 0.80 to 0.95 in Exhibit 7-1(a);
- Grade: 2%, varied from 1% to 6% in Exhibit 7-1(b); and
- Total ramp density: 2 ramps/mi, varied from 1 to 4 ramps/mi in Exhibit 7-1(c).

Exhibit 7-1
Example Sensitivity Analysis for Selected Basic Freeway Segment Model Inputs



(a) Sensitivity to PHF

(b) Sensitivity to Grade



(c) Sensitivity to Total Ramp Density

If varying a single input parameter within its reasonable range results in a 0% to 10% change in the service measure estimate, the model can be considered to have a low degree of sensitivity to that parameter. If a 10% to 20% change in the service measure estimate results, the model can be considered moderately sensitive to that parameter, and if a change greater than 20% results, the model can be considered highly sensitive (*12*).

As shown in Exhibit 7-1(a) and Exhibit 7-1(b), LOS D service volumes for basic freeway segments are moderately sensitive to both PHF and grade across the reasonable ranges of values for those inputs, with the highest service volumes 11% and 14% higher than the lowest service volumes, respectively. Consequently, particular care should be taken to select appropriate values for these inputs.

Exhibit 7-1(c) shows that LOS D service volumes have a low sensitivity to total ramp density, with just a 5% range in the output volumes. Therefore, a close match between the assumed average ramp density value and the future condition is less essential.

Exhibit 7-2 shows an alternative way to visualize results sensitivity, based on the pedestrian link LOS score from Chapter 18, Urban Street Segments. In this example, the number of directional lanes (1), curb lane width (12 ft), and PHF (0.90) are held fixed, and there is assumed to be no bicycle lane, parking lane, or buffer between the sidewalk and the curb lane. The following inputs are varied one at a time:

- Speed limit: 30 mi/h, varied from 20 to 45 mi/h;
- Curb lane traffic volume: 500 veh/h, varied from 50 to 1,000 veh/h; and
- Sidewalk width: 6 ft, varied from 0 to 10 ft.

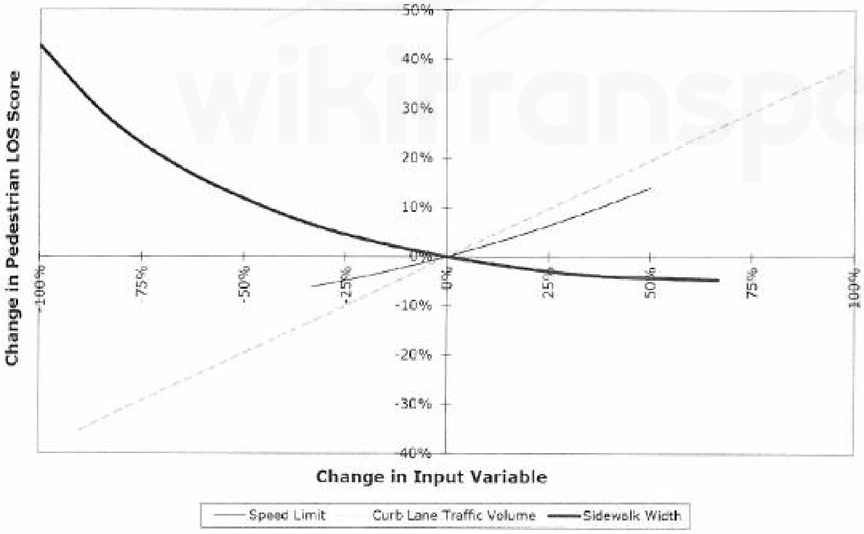
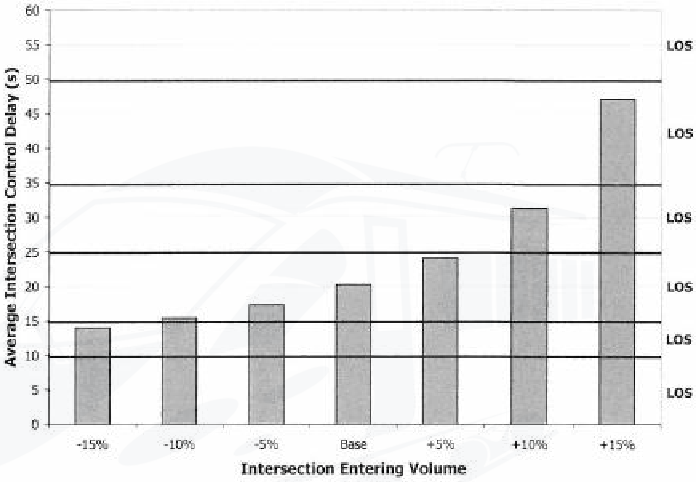


Exhibit 7-2
Example Sensitivity Analysis of Urban Street Link Pedestrian LOS Score

The pedestrian LOS score is relatively insensitive to speed limit, moderately sensitive to sidewalk width (except when a sidewalk is not present), and highly sensitive to curb lane traffic volume. This kind of presentation works best when typical values for the input variables to be tested lie near the middle of their range rather than at or near one of the extremes.

Exhibit 7-3 shows an example of testing the sensitivity of control delay, and the corresponding LOS result, at an all-way STOP-controlled intersection, by varying the demand volumes used in the analysis. In the exhibit, the base volume entering the intersection on all approaches is varied within a ±15% range in 5% increments. This kind of sensitivity analysis is particularly useful in working with forecasts of volume that have a high degree of uncertainty associated with them.

Exhibit 7-3
Example Sensitivity Analysis of All-Way STOP-Control Model Outputs Based on Varying Volume Inputs



Note: Values used in the calculation are four-legged intersection with one lane on each approach, PHF = 0.90, and 2% heavy vehicles. Base volumes are 210 through vehicles, 35 left-turning vehicles, and 35 right-turning vehicles on each approach.

As shown in Exhibit 7-3, under the base volume forecast, the intersection is forecast to operate at LOS C. If future traffic volumes are lower than forecast or as much as 5% higher than forecast, the intersection will still operate at LOS C or better. If future traffic volumes are 10% higher than forecast, the intersection will operate at LOS D; if traffic volumes are 15% higher than forecast, the intersection will operate at LOS E. If the jurisdiction's operations standard for the intersection is LOS E or better, acceptable operation of the intersection could reasonably be expected even if higher volumes than forecast were to occur. However, if the standard was LOS D or better, a closer look at the reasonableness of the volume forecasts might be needed to conclude that the intersection would operate acceptably.

Depending on the model and the specifics of the situation being modeled, relatively small changes in model inputs can have relatively large impacts on model outputs.

ACCURACY AND PRECISION

Overview

Accuracy and precision are independent but complementary concepts. *Accuracy* relates to achieving a correct answer, while *precision* relates to the size of the estimation range of the parameter in question. As an example of accuracy, consider a method that is applied to estimate a performance measure. If the performance measure is delay, an accurate method would provide an estimate closely approximating the actual delay that occurs under field conditions. The precision of the estimate is the range that would be acceptable from an analyst's perspective in providing an accurate estimate. Such a range might be expressed as the central value for the estimated delay plus or minus several seconds.

In general, the inputs used by HCM methodologies come from field data or estimates of future conditions. In either case, these inputs can be expected to be accurate only to within 5% or 10% of the true value. Thus, the computations performed with these inputs cannot be expected to be extremely accurate, and the final results must be considered as estimates that are accurate and precise only within the limits of the inputs used.

HCM users should be aware of the limitations of the accuracy and precision of the methodologies in the manual. Such awareness will help in interpreting the results of an analysis and in using the results to make a decision about the design or operation of a transportation facility.

Calculation Precision Versus Display Precision

Precision in calculation differs from precision in presenting final results.

The extensive use of personal computers has allowed performance measure calculations to be carried to a large number of digits to the right of the decimal point. The final result of calculations performed manually and carried to the suggested number of significant figures may be slightly different from the result of calculations performed on a computer.

Implied Precision of Results

The typical interpretation given to a value such as 2.0 is that the value is in a precision range of two significant figures and that results from calculations should be rounded to this level of precision. The actual computational result would have been in the range of 1.95 to 2.04 by standard rounding conventions. Occasionally, particularly in the running text of the HCM, editorial flexibility allows a zero to be dropped from the number of digits. In most cases, however, the number of the digits to the right of the decimal point does imply that a factor or numerical value has been calculated to that level of precision.

AVERAGE VALUES

Unless specifically noted otherwise, HCM performance measure estimates are average (mean) values.

Unless otherwise noted or defined, numerical values are mean values for the given parameter. Thus, a measure of speed or delay is the mean value for the population of vehicles (or persons) being analyzed. Similarly, a lane width for two or more lanes is the mean (average) width of the lanes. The word "average" or "mean" is only occasionally carried along in the text or exhibits to reinforce this otherwise implicit fact. LOS threshold values, adjustment factors used in computations, and calculated values of performance measures are assumed to represent conditions that have a reasonable expectation of being observed regularly in North America, as opposed to the most extreme condition that might be encountered.

3. DEFINING AND COMPUTING UNIFORM PERFORMANCE MEASURES

The exact definition of performance measures poses an important question, particularly when performance measures produced by different tools are to be compared. Definitions and computational methods are especially important when the LOS must be inferred from another performance measure obtained by alternative methods and applied to the thresholds presented in the HCM's procedural chapters. Often, a performance measure is given the same name in various tools, but its definition and interpretation differ.

This section reviews the key performance measures produced by HCM methodologies and introduces the concept of developing these measures from an analysis of the individual vehicle trajectories produced by microsimulation tools. The most important measures are discussed in terms of uniform definitions and methods of computation that will promote comparability among different tools. More detailed procedures for developing performance measures from individual vehicle trajectories are presented in Chapter 36, Concepts: Supplemental.

PERFORMANCE MEASURES REPORTED BY HCM METHODOLOGIES

The key performance measures reported by the HCM methodologies in Volumes 2 and 3 were summarized in Exhibit 6-6 in Chapter 6, HCM and Alternative Analysis Tools. The applicability of these procedures and alternative tools was indicated for each system element. Exhibit 7-4 includes all of the performance measures identified in Chapter 6. The service measures that determine LOS for each system element are also identified. In this section, the key performance measures are presented in terms of their definitions and computational procedures. The potential for the development of uniform performance measures from alternative tools is presented later in this section.

Exhibit 7-4
Key Performance Measures Reported by HCM Methodologies

Chapter	Density	Speed	v/c Ratio[a]	Travel Time	Control Delay	Queue	Other Measures
10. Freeway Facilities Core Methodology	**Yes**	Yes	Yes	Yes		Yes	[b]
11. Freeway Reliability Analysis		Yes		Yes			[c]
12. Basic Freeway/Multilane Segments	**Yes**	Yes	Yes				
13. Freeway Weaving Segments	**Yes**	Yes	Yes				[d]
14. Freeway Merge/Diverge Segments	**Yes**	Yes	Yes				
15. Two-Lane Highways		**Yes**	Yes				[e]
16. Urban Street Facilities		**Yes**		Yes	Yes		[f]
17. Urban Street Reliability and ATDM		Yes		Yes			[c]
18. Urban Street Segments		**Yes**	Yes	Yes	Yes		[f]
19. Signalized Intersections			Yes		**Yes**	Yes	
20. TWSC Intersections			Yes		**Yes**	Yes	
21. AWSC Intersections			Yes		**Yes**	Yes	
22. Roundabouts			Yes		**Yes**	Yes	
23. Ramp Terminals/Alt. Intersections			Yes	**Yes**	Yes	Yes	
24. Off-Street Pedestrian/Bicycle Facilities							[g]

Notes: v/c = volume/capacity; TWSC = two-way STOP-controlled; AWSC = all-way STOP-controlled; alt. = alternative.
Bold text indicates a chapter's service measure(s).
[a] A v/c ratio greater than 1.00 is often used to define LOS F conditions. All chapters that produce a v/c ratio also produce an estimate of capacity.
[b] Vehicle miles, vehicle hours.
[c] Measures related to travel time reliability.
[d] Weaving speed, nonweaving speed.
[e] **Percent time-spent-following.**
[f] Stop rate, running time.
[g] **Meeting and passing events.**

Speed-Related Measures

Speeds are reported in several chapters of this manual:

- *Chapter 10, Freeway Facilities,* uses the average speeds computed by the other freeway chapters when all segments are undersaturated. When demand exceeds capacity, the speeds on the affected segments are modified to account for the effects of slower-moving queues.
- *Chapter 11, Freeway Reliability Analysis,* and *Chapter 17, Urban Street Reliability and ATDM,* consider the effects of traffic demand variability, weather, incidents, work zones, and traffic management strategies on the day-to-day variation in observed speeds and travel times on a roadway.
- *Chapter 12, Basic Freeway and Multilane Highway Segments,* estimates the average speed on the basis of the free-flow speed and demand volume by using empirically derived relationships.
- *Chapter 13, Freeway Weaving Segments,* estimates the average speed as a composite of the speeds of weaving and nonweaving vehicles on the basis of free-flow speed, demand volumes, and geometric characteristics. The method for estimating the actual speeds is based on the nature of the weaving segment and the origin–destination matrix of traffic entering and leaving the segment. The speed estimation processes are substantially more complex in weaving segments than in basic freeway segments.
- *Chapter 14, Freeway Merge and Diverge Segments,* estimates the average speed of vehicles across all lanes as well as the average speeds in the lanes adjacent to the ramp. The computations are based on empirical relationships specifically derived for merge and diverge segments.
- *Chapter 15, Two-Lane Highways,* treats the average travel speed (ATS) on certain classes of highways as one determinant of LOS. The ATS is determined as an empirical function of free-flow speed, demand flow rates, proportion of heavy vehicles, and grades.
- *Chapter 16, Urban Street Facilities,* uses through-vehicle travel speed to determine LOS.
- *Chapter 18, Urban Street Segments,* also uses through-vehicle speed to determine LOS. The average speed is computed by dividing the segment length by the average travel time. The average travel time is determined as the sum of

  1. Time to traverse the link at the running speed, which is computed as a function of the free-flow speed, demand flow rate, and geometric factors;
  2. Control delay due to the traffic control device at the end of the segment; and
  3. Midblock delay due to access points.

  The average speed applies only to arterial through vehicles and not to the traffic stream as a whole.

Travel Time Reliability–Related Measures

Reliability measures are defined and computed for freeway facilities and urban street facilities. As described previously in Section 2 of Chapter 4, Traffic Operations and Capacity Concepts, a variety of travel time reliability measures can be developed from a travel time distribution. The HCM computes this distribution by repeatedly applying the freeway facility or urban streets method, while varying the inputs to reflect fluctuations in demand over the course of a longer period (e.g., a year), along with fluctuations in roadway capacity and free-flow speed due to severe weather, incidents, and work zones.

The measures produced by the freeway facilities and urban street facilities methods can be categorized as either (*a*) measures of travel time variability or (*b*) the success or failure of individual trips in meeting a target travel time or speed. Examples of the former include the travel time index, the planning time index, the reliability rating, the standard deviation of travel times, and the misery index. Examples of the latter include percent of on-time trips (based on a target maximum travel time for a facility) and percent of trips with average travel speeds less than a minimum target value.

Queue-Related Measures

Queue measures are defined and computed for both interrupted- and uninterrupted-flow facilities. Queues may be defined in terms of the number of vehicles contained in the queue or the distance of the last vehicle in the queue from the end of the segment (i.e., back of queue or BOQ).

Because of the shock waves that form as vehicles depart the front of the queue and new vehicles join the back of the queue, the location of the BOQ with respect to a reference point (e.g., an intersection stop bar) is typically *not* equal to the number of queued vehicles multiplied by an average length per vehicle. For example, at a signalized intersection, the maximum number of vehicles in queue occurs at the end of red, but the BOQ continues to move backwards during the subsequent green phase, as vehicles continue to join the BOQ while the queue is dissipating from the front.

The probability of the BOQ reaching a specified point where it will cause problems is of most interest to the analyst. For most purposes, the BOQ is therefore a more useful measure than the number of vehicles in the queue.

Queue measures are reported by the following procedures in this manual:

- *Chapter 10, Freeway Facilities Core Methodology*: Queuing on freeway facilities is generally the result of oversaturation caused by demand exceeding capacity. As such, it is treated deterministically in Chapter 10 by an input–output model that tracks demand volumes and actual volume served through the bottleneck. The propagation and dissipation of freeway queues are estimated from a modified cell transmission model. The speed at which queues grow and shrink is calculated from a macroscopic simulation of the queue accumulation process, which depends, among other factors, on the bottleneck demand, the bottleneck capacity, and the jam density. Residual demand is processed in subsequent time intervals as demand levels drop or the bottleneck capacity increases. Generally, a drop in demand results in a queue that clears from the back, while an increase in bottleneck capacity, typically when incidents clear, results in a forward-clearing queue. The queue's spatial extent is calculated from the number of queued vehicles and the storage space on the facility (i.e., the length and number of lanes). The queue's temporal duration is a function of demand patterns and bottleneck capacity. The presence of a queue on a given segment also affects the rate at which vehicles can flow into the next segment. The volume arriving in downstream segments may therefore be less than the demand volume. Downstream segments with demand volumes greater than capacity may turn out to be hidden bottlenecks if a more severe upstream bottleneck meters the volume served.

- *Chapter 19, Signalized Intersections*: The cyclical maximum BOQ is computed on the basis of a queue accumulation and discharge model with a correction applied to account for acceleration and deceleration. Random arrivals and oversaturated conditions are accommodated by correction terms in the model. The computational details are provided in Chapter 31, Signalized Intersections: Supplemental. The measure reported for signalized approaches is the average BOQ. Percentile values are also reported.
- *Chapters 20 to 22, unsignalized intersections*: The 95th percentile queue length (i.e., number of queued vehicles) is computed by deterministic equations as a function of demand volume, capacity, and analysis period length.
- *Chapter 23, Ramp Terminals and Alternative Intersections*: This chapter uses the BOQ calculations for signalized intersections or roundabouts, depending on the intersection form. The queue storage ratio—the average BOQ divided by the available storage length—helps determine LOS F.

Stop-Related Measures

Stop-related measures are of interest to analysts because of their comfort, convenience, cost, and safety implications. An estimate of the number of stops on a signalized approach is reported by the signalized intersection analysis procedure described in Chapter 19, with details given in Chapter 31. Chapter 18, Urban Street Segments, incorporates the stops at the signal into a "stops per mile" rate for each segment. Other chapters do not report the number of stops. Most alternative tools based on both deterministic and simulation models produce an estimate of the number of stops for a variety of system elements by using the tools' own definitions, and most tools allow user-specified values for the parameters that define when a vehicle is stopped.

The Chapter 19 procedure defines a "partial" stop as one in which a vehicle slows as it approaches the BOQ but does not come to a full stop. Some alternative tools, both deterministic and simulation based, consider a partial stop to be a later stop after the first full stop.

The definition and computation of delay vary widely among tools.

Delay-Related Measures

Because of multiple definitions and thresholds, delay is one of the most difficult measures to compare among traffic analysis tools. Delay measures are reported by the same chapters in this manual that report queue measures:

- *Chapter 10, Freeway Facilities Core Methodology,* calculates delay on a globally undersaturated freeway facility from the sum of all individual segment delays. The segment delays are calculated from the travel time difference between the segment operating at free-flow speed and the segment operating at the calculated space mean speed. For undersaturated conditions, the segment space mean speed is calculated from the segment-specific methodologies in Chapters 12 to 14. For oversaturated conditions, the segment speed is estimated from the prevailing density on the segment. The travel time difference is multiplied by the number of vehicles in a segment during each time period to obtain the total vehicle hours of delay per segment and per time period. The total vehicle hours of delay on the facility for each time period and for the entire analysis are obtained by summation.
- *Chapter 19, Signalized Intersections,* calculates LOS from control delay. Control delay is computed on the basis of an incremental queue analysis technique by using a queue accumulation and discharge model. Random arrivals and oversaturated conditions are accommodated by correction terms in the model. A separate correction is applied to account for an initial queue left from a previous interval. The details of the computation are provided in Chapter 31, Signalized Intersections: Supplemental.
- *Chapters 20 to 22, unsignalized intersections,* calculate LOS from control delay. The control delay is computed by deterministic equations as a function of demand volume, capacity, and analysis period length. The LOS thresholds for unsignalized intersections are different from those for signalized intersections.
- *Chapter 23, Ramp Terminals and Alternative Intersections,* calculates LOS from the average travel time experienced by an origin–destination demand as it travels through the interchange.

Density-Related Measures

Density is expressed in terms of vehicles per mile per lane and is generally recognized as an unambiguous indicator of congestion. Density is used as the determinant of LOS A through E for freeway and multilane highway segments. It is conceptually easy to define and estimate, but the question is how to apply density to the right section of roadway over the right period of time.

The procedures for different types of freeway segments follow a density estimation process that is specific to each segment type:

- *Chapter 10, Freeway Facilities Core Methodology,* determines density for undersaturated conditions by applying the procedures given in Chapters 12 to 14. When queuing occurs as a result of oversaturation caused by excessive demand or by bottlenecks, the density is determined by the queue tracking procedures described previously for freeway facilities.

- *Chapter 12, Basic Freeway and Multilane Highway Segments,* determines speeds and demand flow rates that are adjusted for a variety of geometric and operational conditions. The segment density is computed by dividing the adjusted flow rate by the estimated speed. Empirical relationships are used throughout the chapter for computations and adjustments.
- *Chapter 13, Freeway Weaving Segments,* also determines density by dividing the adjusted demand flow rate by the estimated speed. The speed estimation process was described previously.
- *Chapter 14, Freeway Merge and Diverge Segments,* bases the LOS assessment on the density in the two lanes adjacent to the ramp lanes. The density is estimated directly by using empirically derived relationships that depend on the ramp and freeway (Lanes 1 and 2) volumes and the length of the acceleration or deceleration lane. Several operational and geometric factors affect the computations.

USE OF VEHICLE TRAJECTORY ANALYSIS IN COMPARING PERFORMANCE MEASURES

This section explores the use of vehicle trajectory analysis to define and estimate consistent performance measures. It first introduces the mathematical properties of trajectories as an extension of the visual properties. It identifies the types of analyses that can be performed and provides examples that illustrate how trajectory analysis can be applied. A later section identifies the performance measures that can be computed from individual vehicle trajectories and explores their compatibility with the performance measures estimated by the HCM's computational procedures. Specific trajectory analysis procedures by which consistent performance measures can be estimated are presented in Section 5 of Chapter 36, Concepts: Supplemental.

The concept of individual vehicle trajectory analysis was introduced in Chapter 4, Traffic Flow and Capacity Concepts. According to that chapter, a growing school of thought suggests that a comparison of results between traffic analysis tools and methods is possible only through an analysis of vehicle trajectories as the "lowest common denominator." Trajectory-based performance measures can be made consistent with HCM definitions, with field measurement techniques, and with each other. Examples of vehicle trajectory plots were shown in Chapter 4 to illustrate the visual properties of vehicle trajectories.

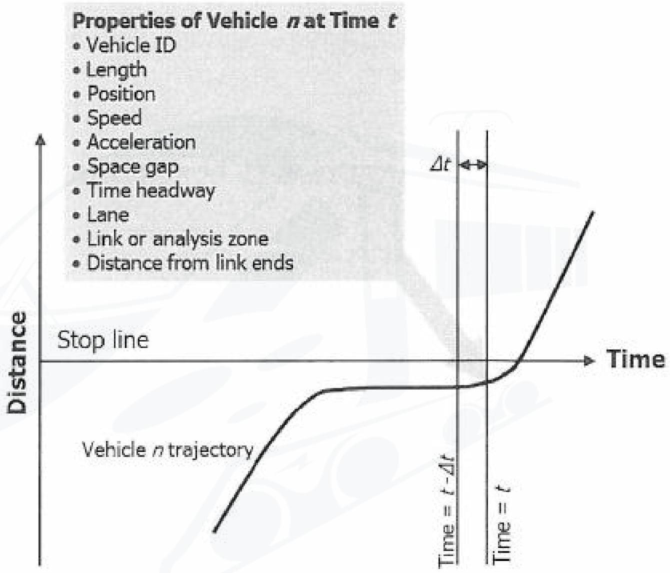
Mathematical Properties of Vehicle Trajectory

While the trajectory plots presented in Chapter 4 provide a good visual insight into operations, they do not support quantitative assessments. To develop performance measures from vehicle trajectories, the trajectories must be represented mathematically and not just visually. A mathematical representation requires development of a set of properties that are associated with each vehicle at specific points in time and space.

Exhibit 7-5 shows the trajectory of a single vehicle through a traffic signal. At each point in time, a number of properties may be determined. The trajectory for the vehicle is quantified through a list of the properties of vehicle n at each point in time. One important parameter in the quantification of trajectories is the time increment between sampling points, represented in Exhibit 7-5 as Δt. Time increments in typical simulation tools currently range from 0.1 to 1.0 s. Smaller values are gaining acceptance within the simulation modeling community because of their ability to represent traffic flow with greater fidelity.

Many properties can be associated with a specific vehicle at a point in time. Some properties are required for the accurate determination of performance measures from trajectories. Others are used for different purposes such as safety analysis. The important properties for estimating consistent performance measures are indicated in Exhibit 7-5.

Exhibit 7-5
Mathematical Properties of Vehicle Trajectories



Longitudinal and Spatial Analysis

Longitudinal and spatial analysis of vehicle trajectories must be distinguished at the outset. Longitudinal analysis involves following the position of vehicles as they traverse a segment. This type of analysis determines delay-related measures of various types and stop-related measures. Driver comfort, safety, and environmental measures may also be determined by longitudinal analysis, but these measures are beyond the scope of the HCM.

Spatial analysis, on the other hand, involves considering all the vehicles on a segment at a specific time step. The two principal spatial measures are density and queue lengths. Both types of analysis are examined here.

Limitations of Vehicle Trajectory–Based Analysis

The procedures described here and in Chapter 36 are intended to produce performance measures from vehicle trajectories that are based on the definitions of traffic parameters given in this manual to promote uniformity of reporting among different simulation tools. The results should improve the acceptance of simulation tools for highway capacity and LOS analysis. However, the term "HCM-compatible" does not suggest that the numerical values of measures produced by a simulation tool will be identical to those from the HCM or to those from other simulation tools. Several factors must be considered.

Traffic Modeling Differences

The trajectory information is produced by the simulation model. Each simulation tool has its own models of driver behavior. It is not practical or desirable to prescribe simulation modeling details in this document. Developers continually strive to improve the realism of their products to gain a competitive advantage in the market. The Next Generation Simulation Program (*13*) has had some success in developing core algorithms to be shared by simulation developers, but a universal simulation model is not a practical objective.

Approximations in Trajectory Analysis

Chapter 4 pointed out that all performance measures reported by deterministic models, simulation models, and field observations represent an approximate assessment of field conditions. The need for approximations in trajectory analysis to promote uniform reporting is explored in more detail in Chapter 36. One problem is that the procedures prescribed in this manual introduce approximations that cannot be replicated in simulation because of conceptual differences and model structure.

Differences That Are Unrelated to Trajectory Analysis

The use of vehicle trajectories addresses some, but not all, of the sources of difference in the definition of performance measures. For example, the temporal and spatial boundaries of an analysis tend to be defined differently by different tools. Use of the performance measure definitions and guidelines presented in this manual in conducting simulation analyses is important to HCM compatibility.

Examples of Vehicle Trajectory Data

Simulation tools propagate vehicles through a roadway segment by periodically updating and keeping track of the trajectory properties that are maintained internally within the traffic flow model. Several examples of the analysis of vehicle trajectories on both interrupted- and uninterrupted-flow facilities are provided in Chapter 36. The examples demonstrate the complexities that can arise in certain situations, especially when demand exceeds capacity.

Two examples included in Chapter 36 are presented here to illustrate how vehicle trajectories can be obtained from simulation tools. The first is shown in Exhibit 7-6, which presents the simplest possible case, involving an approach with only one lane. The simulation parameters were constrained to remove all randomness in the arrival and departure characteristics. While this situation might appear to be trivial, it is the basis of the signalized intersection delay analysis procedure summarized in Chapter 19 and described in more detail in Chapter 31.

The trajectories may be analyzed longitudinally to produce estimates of delays and stops. They may also be analyzed spatially to produce instantaneous queue length estimates.

A more complex situation is depicted in Exhibit 7-7, which illustrates the vehicle trajectories associated with queue backup from a downstream signal. The randomness of arrivals and departures was restored to this case.

Exhibit 7-6
Trajectory Plot for Uniform Arrivals and Departures

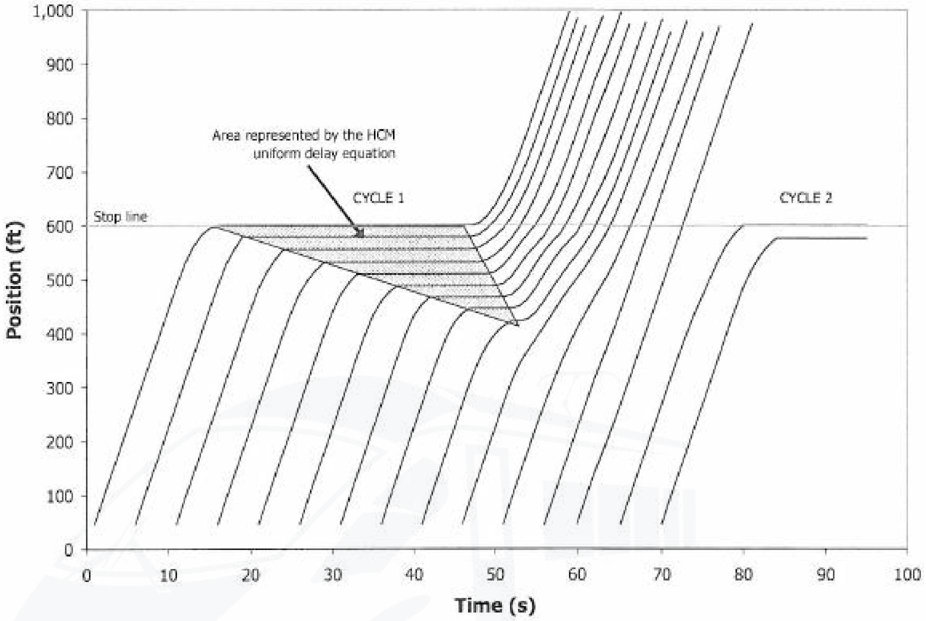
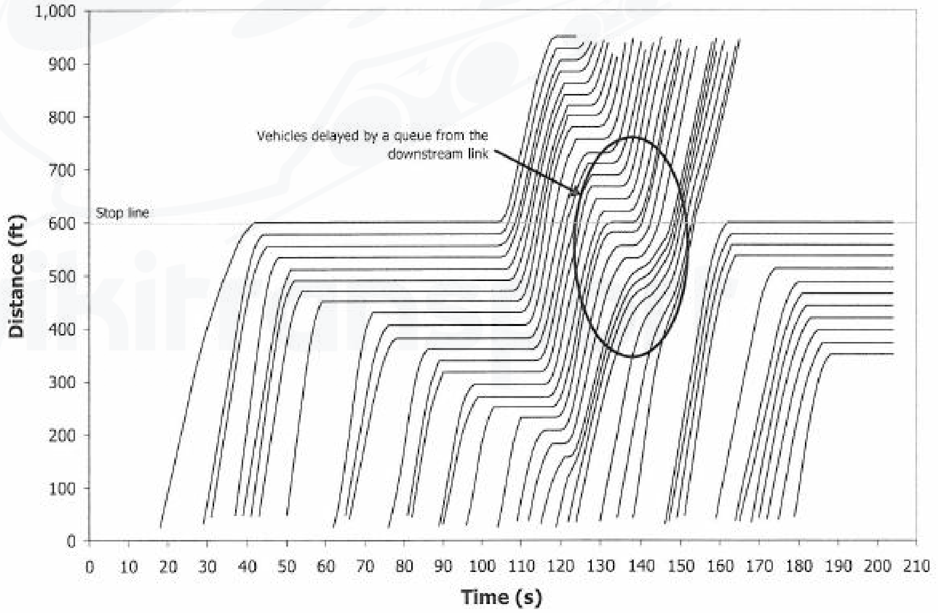


Exhibit 7-7
Queue Backup from a Downstream Signal



The important difference in Exhibit 7-7 from the simple case presented in Exhibit 7-6 is that backup into a specific segment from a downstream segment is not covered by the signalized intersection analysis methods in Chapters 19 and 31. However, the performance measures may be estimated by trajectory analysis.

REQUIREMENTS FOR COMPUTING PERFORMANCE MEASURES BY VEHICLE TRAJECTORY ANALYSIS

Most performance measures reported by the procedures in this manual are also reported by simulation tools. This section identifies the general requirements for computing measures from simulation by using individual vehicle trajectories to achieve comparability between traffic analysis tools. More detailed procedures are presented in Chapter 36.

General Trajectory Analysis Guidelines

The following general guidelines apply to trajectory analysis procedures.

1. The trajectory analysis procedures are limited to the analysis of trajectories produced by the traffic flow model of each simulation tool. The nature of the procedures does not suggest the need for developers to change their driver behavior or traffic flow modeling logic.
2. If the procedures for estimating a particular measure cannot be satisfactorily defined to permit a valid comparison between the HCM and other modeling approaches, then such comparisons should not be made.
3. All performance measures that accrue over time and space shall be assigned to the links and time intervals in which they occur. Subtle complexities make it impractical to do otherwise. For example, the root cause of a specific delay might not be within the link or the immediate downstream link. The delay might be secondary to a problem at some distant location in the network and in a different time interval.
4. The analyst must understand that the spatial and temporal boundaries of the analysis domain must include a period that is free of congestion on all sides. This principle is also stated in Chapter 10 for analysis of freeway facilities and in Chapter 19 for multiperiod signalized intersection analysis. To ensure that delays to vehicles that are denied entry to the system during a given period are properly recognized, creation of fictitious links outside of the physical network to hold such vehicles might be necessary. A more detailed discussion of spatial and temporal boundaries is provided later in this section.
5. Proper initialization or "seeding" of the network before trajectory analysis is performed is important. In setting and applying the warm-up periods, simulation tools typically start with an empty network and introduce vehicles until the vehicular content of the network stabilizes. Trajectory analysis should not begin until stability has been achieved. If the simulation period begins with oversaturated conditions, stability may never be achieved. See the discussion later in this section on temporal and spatial boundaries.

Speed- and Travel Time–Related Measures

Speed and travel time are treated together because, at least for segment values, they are closely related. The average speed of a vehicle traversing a segment may be determined by dividing the segment length by the travel time.

Macroscopic segment travel time estimation does not require a detailed trajectory analysis. The travel time for an individual vehicle may be computed for a given segment by subtracting the time when the vehicle entered the segment from the time when it left the segment. The average travel time may be computed as the mean of the individual travel times; however, this technique is valid only for complete trips (i.e., those that have entered and left the segment).

The space mean speed for all vehicles within the segment during the time period may be estimated by dividing the total vehicle miles of travel by the total vehicle hours of travel time. The total vehicle miles and vehicle hours may be accumulated by including all the vehicles and time steps in the analysis domain. See the discussion later in this section on spatial and temporal boundaries.

Queue-Related Measures

Because of their microscopic nature, simulation tools can produce useful measures of queuing that are beyond the limits of those described in the HCM's procedural chapters. However, these queue-related performance measures are difficult to compare with those derived from the HCM. No comparisons should be attempted without a detailed knowledge of a specific tool's queue definitions and computations. With consistent definitions, more uniform queue measures could be obtained from simulation tools.

Queued State

What defines entry to and exit from a queue? Several definitions are applied by different tools for this purpose. The definition given in Chapter 31 for purposes of field observations states the following:

> A vehicle is considered as having joined the queue when it approaches within one car length of a stopped vehicle or the stop bar and is itself about to stop. This definition is used because of the difficulty of keeping track of the moment when a vehicle comes to a stop.

Chapter 31's definition of the exit from a queue, also intended for field study applications, is more complex and offers some interesting challenges for implementation in both deterministic and simulation models. As a practical approximation, a vehicle should be considered to have left the queue when it has left the link in which it entered the queue. When a queue extends the full length of a link, a vehicle should be considered to enter the queue at the time it enters the link. Other conditions, such as a lane change to escape a queue, might also signal the exit from a queue. These conditions are discussed in Section 5 of Chapter 36: Concepts: Supplemental.

Queue Length

Queue length estimation is generally required to determine whether a queue has reached the point where it will interfere with other traffic movements. Queue length computations are applied at a macroscopic level by HCM procedures. Simulation models, on the other hand, can establish the instantaneous BOQ at each point in time. The question is how to process the instantaneous values in a manner that will produce meaningful results.

Queue length analysis by simulation must be treated differently for different conditions. There are three cases to consider:

1. *Undersaturated noncyclical operation*, typical of operation with isolated two-way STOP control: In this case, the queue accumulation and discharge follow a more or less random pattern. The Chapter 20 method estimates the 95th percentile queue length on the basis of a deterministic average queue length modified by a term that accounts for random arrivals. This process could be approximated in trajectory analysis by establishing a distribution of instantaneous queue lengths by time step. The 95th percentile queue length could be determined from that distribution.
2. *Undersaturated cyclical operation*, typical of operation at a traffic signal: In this case, a maximum BOQ is associated with each cycle. The maximum BOQ in each cycle represents one observation for statistical analysis purposes. The use of a distribution of instantaneous values is not appropriate here because the queue accumulation and discharge are much more systematic than random. Including instantaneous queue lengths that occur when the queue is expected to be zero (i.e., at the end of the green) would underestimate the measure of interest, which is the peak queue length. With a sufficient number of cycles, a distribution of peak queue lengths with a mean value and a standard deviation could be established. The probability of queue backup to any point could then be estimated from this distribution.
3. *Oversaturated operation*, either cyclical or noncyclical: When demand exceeds the capacity of an approach or system element, the queue will grow indefinitely. For purposes of simulation, the measure of interest is the residual BOQ at the end of the simulated interval and the effect of the queue on upstream segments. These considerations are especially important in multiperiod analyses.

The undersaturated condition might include brief periods of queue buildup and discharge as long as continuous buildup and residual queues do not occur.

Stop-Related Measures

Most alternative tools based on both deterministic and simulation models produce an estimate of the number of stops by their own definition, and most allow user-specified values for the parameters that establish the beginning and end of a stop. Stop-related measures are of interest to analysts because of their comfort, convenience, cost, emissions, and safety implications.

Definition of the Stopped State

The definition of when a vehicle is stopped has the same two elements as the definition of when it is queued—that is, when does the stop begin and when does it end? Speed thresholds are often used to determine when a vehicle is stopped. The only nonarbitrary threshold for this purpose is zero. However, practical considerations suggest that simulation modeling algorithms dealing with stopping would be more stable if a near-zero speed were used instead. Chapter 19 applies a speed of 5 mi/h in determining when a vehicle has stopped.

There are two different modeling purposes for releasing a vehicle from the stopped state:

- To terminate the accumulation of stopped delay, and
- To enable the accumulation of subsequent stops.

The first condition is easier to deal with in the trajectory analysis. When the vehicle is no longer stopped, it should no longer accumulate stopped delay. The logical speed threshold for this condition is the same speed threshold that established the beginning of the stop.

Estimating the Number of Stops

The accumulation of multiple stops poses more problems and generally relies on arbitrary thresholds that vary among different tools. The main problem with multiple stops is that stops after the first take place from a lower speed and therefore have a less adverse effect on driver comfort, operating costs, and safety. For signalized approaches, some tools apply a "probability of stopping" model in which the maximum probability is 100% and, therefore, the maximum number of stops is 1.0 on any approach. Other tools model subsequent stops on the basis of the release from the stopped state when the vehicle reaches an arbitrary threshold speed, often around 15 mi/h.

While the number of stops is an important performance measure, the values produced by different tools are difficult to compare. Such comparisons should not be attempted without adequate knowledge of the definitions and parameters used by a specific tool.

Delay-Related Measures

Practically all traffic analysis tools produce a performance measure called "delay," but tools vary widely in the definition and computation of delay. This discussion suggests consistent definitions for delay.

Delay Definitions

Delay is generally defined as the excess time spent on a road segment compared with the time at a target speed that represents a zero-delay condition. The target speed is the speed at which a specific driver prefers to drive. Different tools have different definitions of target speed. Some are driver- and vehicle-specific, taking into account driver aggressiveness and roadway characteristics. Because target speed is a function of individual driver behavior, there will be some differences in the method of computation, especially if the target speed is different for each vehicle. For tools that require a user-specified free-flow speed as an input, the methodology presented in the procedural chapters of this manual should be used to determine the free-flow speed.

The time a vehicle spends on a segment is easy to determine from its trajectory. On the other hand, the target time is subject to a number of definitions:

- *Travel time at ideal speed*: usually the free-flow speed.
- *Travel time at the individual vehicle's target speed*: a function of the free-flow speed, prevailing roadway and traffic conditions, and the driver's characteristics.
- *Travel time at 10 mi/h below speed limit*: used by some transportation agencies to determine whether a trip is "on time" for travel time reliability reporting. When it is compared with the travel time at ideal speed, this measure establishes "on-time delay."
- *Travel time at a specified travel time index*: The travel time index is the ratio of actual travel time to ideal travel time. It is used primarily for reporting congestion in nationwide mobility monitoring. A travel time index of 1.33 or 1.5 is sometimes taken as an indication of freeway congestion. This measure establishes congestion delay. It is intended to be an indicator of the need for roadway improvements.
- *Travel time without traffic control*: This measure establishes control delay. Unlike the previous measures, which are applied to an entire segment, control delay is applied only to the portion of the segment where a queue is present. Control delay is a subset of segment delay because it does not include the delays caused by traffic interactions upstream of the queue. The definition applies uniformly to all types of control, including signals, stop signs, and roundabouts.

In all cases, a lower limit of zero must be imposed when the actual travel time is shorter than the reference time.

Aggregated Delay Versus Unit Delay

The difference between aggregated delay, usually expressed in vehicle hours, and unit delay, usually expressed in seconds per vehicle, should be noted. Aggregated delay is generally used to assess the operating costs associated with a candidate treatment, because an economic value can be assigned to a vehicle hour of delay. Unit delays are associated with driver perception of the LOS on a facility. For these two definitions to be dimensionally consistent, the unit delays must actually be expressed in vehicle seconds per vehicle. Common practice, however, is to shorten the definition to seconds per vehicle to promote public understanding.

Representation of Delay by Vehicle Trajectories

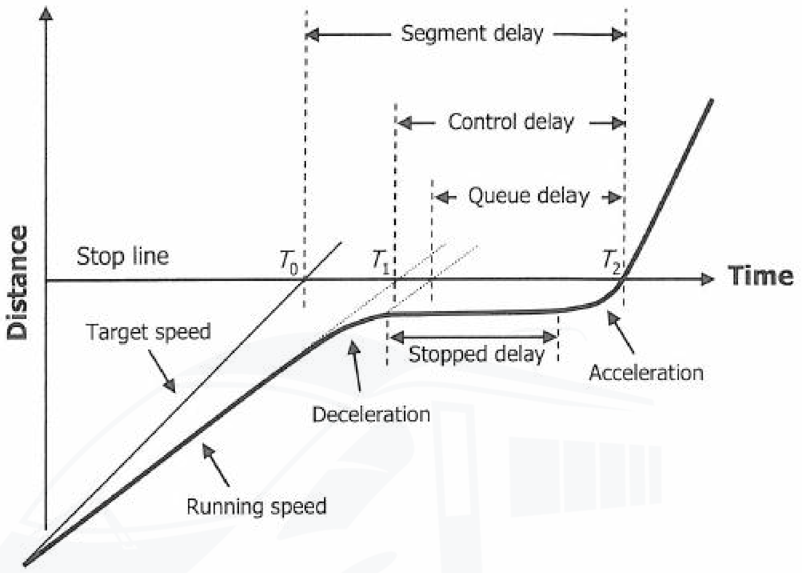
Several delay definitions were presented previously. These definitions may be interpreted in terms of vehicle trajectories on the basis of longitudinal trajectory analysis. In all cases, the delay is determined for each time step and accumulated over the entire time the vehicle was in a specified segment.

Exhibit 7-8 illustrates the various ways delay may be defined. Three points are defined in this figure.

- T_0, the time at which a vehicle would have arrived at the stop line if it had been traveling at the target speed;

- T_1, the time at which a vehicle would have arrived at the stop line if it had been traveling at the running speed, which is generally less than the target speed because of traffic interactions; and
- T_2, the time at which a vehicle is discharged at the stop line.

Exhibit 7-8
Definition of Delay Terms in Time and Space



The delay measures defined in terms of the time differences shown in Exhibit 7-8 include the following:

- *Control delay*: defined as $T_2 - T_1$. This delay definition is the one used by the procedure for assessing LOS at controlled intersections and roundabouts.
- *Segment delay*, defined as $T_2 - T_0$. This definition is more commonly used by simulation tools. It reflects the delay experienced by each vehicle since it left the upstream node (usually another signal). Segment delay includes control delay plus all other delay due to traffic interactions.

Two other delay definitions that are based on more complex properties of the vehicle trajectories are shown in Exhibit 7-8:

- *Stopped delay*, which reflects the amount of time a vehicle was actually stopped. The beginning and end of a stop are generally based on speed thresholds, which may differ among tools. In some cases, the threshold speeds are user definable.
- *Queue delay*, which reflects the amount of time a vehicle spends in a queued state. The properties of the trajectory that define a queued state in different tools include speed, acceleration, spacing, and number of vehicles sharing these properties. For trajectory analysis purposes, the queued state was defined previously in this chapter, and this definition is reflected in Exhibit 7-8.

For simulation tools that report total segment delay but do not report control delay explicitly, approximate estimates of control delay can be produced by performing simulation runs with and without the control device(s) in place. The segment delay reported with no control is the delay due to geometrics and interaction between vehicles. The additional delay reported in the run with the control in place is, by definition, the control delay. For short segments with low to medium volumes, the segment delay usually serves as an approximation of the control delay.

The development of control delay estimates by a multiple-run procedure is primarily of academic interest because of the amount of effort involved. The objective at this point is to develop a specification for estimating control delay from vehicle trajectories that may be internalized by simulation model developers to produce HCM-compatible results.

Computational Procedures for Delay-Related Measures

The procedures for computing delay from vehicle trajectories involve aggregating all delay measures over each time step. Therefore, the results take the form of aggregated delay and not unit delay, as defined earlier. To determine unit delays, the aggregated delays must be divided by the number of vehicles involved in the aggregation. Partial trips made over a segment during the time period add some complexity to unit delay computations.

The following procedures should be used to compute delay-related measures from vehicle trajectories:

- *Time step delay*: The delay on any time step is, by definition, the length of the time step minus the time it would have taken the vehicle to cover the distance traveled in the step at the target speed. This value is easily determined and is the basis for the remainder of the delay computations.
- *Segment delay*: Segment delay is represented by the time taken to traverse a segment minus the time it would have taken to traverse the segment at the target speed. The segment delay on any step is equal to the time step delay. Segment delays accumulated over all time steps in which a vehicle is present on the segment represent the segment delay for that vehicle.
- *Queue delay*: The queue delay is equal to the time step delay on any step in which the vehicle is in a queued state; otherwise, it is zero. Queue delays are accumulated over all time steps while the vehicle is in a queue.
- *Stopped delay*: The stopped delay is equal to the time step delay on any step in which the vehicle is in a stopped state; otherwise, it is zero. Since a vehicle is considered to be stopped if it is traveling at less than a threshold speed, a consistent definition of stopped delay requires that the travel time at the target speed be subtracted. Time step delays accumulated over all time steps in which the vehicle was in the stopped state represent the stopped delay. Earlier versions of this manual defined stopped delay as 76% of the control delay, on the basis of empirical data.

Queue delay computed from trajectory analysis provides the most appropriate representation of control delay.

- *Control delay*: Control delay is the additional travel time caused by operation of a traffic control device. The queue delay computed from vehicle trajectories provides a reasonable approximation of control delay when the following conditions are met:
  1. Queue delay is caused by a traffic control device, and
  2. Identification of the queued state is consistent with the definitions provided in the HCM.

Special Delay Estimation Issues

Control delay cannot be computed from individual vehicle trajectory analysis in a manner consistent with HCM procedures that report control delay. It was demonstrated earlier in this chapter (see Exhibit 7-6) that the uniform delay term d_1 described in Chapter 19 is derived from trajectory analysis. The problem is that the delay adjustment terms d_2 and d_3 are macroscopic corrections that have been derived analytically. As such, they cannot be represented by vehicle trajectories. When demand volumes approach and exceed capacity, the correction terms become very large.

Exhibit 7-8 showed the trajectory of a single vehicle in an undersaturated situation. This figure indicates that the control delay will be the same as the queue delay when their travel times projected to the stop line at the running speed (i.e., the broken lines) follow the same path. The problem is that the additional delays from the d_2 and d_3 adjustment terms are not represented in the figure. The adjustment terms are represented implicitly in the queue delays produced by trajectory analysis. As such, they remain a valid estimator of control delay at all levels of saturation.

While the queue delay from trajectory analysis generally provides a reasonable estimate of the delay on a controlled link, certain phenomena raise interpretation issues. The first is geometric delay, which is not included in the Chapter 19 procedure. For example, a large truck turning right can cause additional delay to vehicles in a queue behind it. The additional delay, which would be ignored by the Chapter 19 control delay calculations, would be interpreted by trajectory analysis as control delay. This situation would cause problems in comparing the control delay estimates from the two methods.

Another problem arises with oversaturated conditions. The conceptual differences between Chapter 19's analytical delay model and the microscopic simulation approach make comparison of their results difficult. The comparison becomes even more complicated when queues extend into upstream links.

Reliability-Related Measures

The HCM's conceptual framework for evaluating travel time reliability can be applied to alternative analysis tools. Since the HCM's reliability measures are facility-level measures, only the travel times associated with vehicles that have traveled the full length of the facility should be used in developing the travel time distribution. An earlier subsection provided guidance on calculating HCM-compatible travel times. In addition, some reliability performance measures are indices that are linked to the facility's free-flow speed. The previous subsection on delay-related measures provided guidance on calculating HCM-compatible free-flow or target speeds.

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

Density-Related Measures

Density is one of the easiest measures to compute from vehicle trajectories because it involves simply counting the vehicles in a section of roadway at a specific time. Density is therefore a product of spatial analysis as opposed to longitudinal analysis. The question is how to apply the proper definition of density to the right section of roadway over the right period of time. For example, a main obstacle in comparing densities reported by the procedural chapters in this manual with those reported by simulation tools is their different definitions. The procedures in this manual report density in terms of passenger cars per mile. Simulation tools report this measure in terms of actual vehicles per mile. The simulated densities must be converted to passenger cars per mile to produce comparable results. Procedures for conversion are discussed in Chapter 36, Concepts: Supplemental.

Simulated densities must be converted to passenger cars per mile to produce results comparable with the HCM.

Because of the importance of density as a determinant of LOS, establishment of HCM-compatible trajectory analysis is desirable so that simulated densities can be used for LOS estimation. Microscopic simulation models establish the position of all vehicles in the system at all points in time, making it easy to define and compute density measures that are uniform among different tools by simply counting the number of vehicles on a specified portion of a roadway.

Computational Procedures

The equivalent density in a section can be determined by simulation by using a simple equation that relates density to the spacing of vehicles:

$$\text{Density (veh/mi)} = \frac{5{,}280\ \text{ft/mi}}{\text{vehicle spacing (ft/veh)}}$$

Equation 7-1

Density can also be computed macroscopically at the segment level simply by counting the number of vehicles present on the segment during a given time step. The densities by time step may be aggregated over an analysis period by computing the arithmetic mean of the time step densities. This method of measurement and aggregation should produce HCM-compatible density values in both definition and computation, provided that the demand d does not exceed the capacity c. For d/c ratios greater than 1.0, the density at the end of the analysis period may be of more interest than the average density.

Density is computed on a per lane basis in the examples given in Chapter 36. The combined density for the ramp influence area (the two freeway lanes adjacent to the ramp plus auxiliary lanes, if any, within 1,500 ft of the ramp junction) is also computed because of its application to freeway merge and diverge ramp junctions. To compute the average density for a series of segments in a freeway facility, the procedure outlined in Chapter 10 should be used.

Follower Density

This measure is defined in terms of the number of followers per mile on a two-lane highway. Follower density is not reported in the HCM. Instead, percent time-spent-following is used as a determinant of LOS for two-lane highways in Chapter 15. The definition of the following state is given in Chapter 15 as a condition in which a vehicle is following its leader by no more than 3 s. The concept of follower density has attracted increasing international interest. It is a measure that could be easily derived from trajectory analysis.

STOCHASTIC ASPECTS OF SIMULATION ANALYSIS

The HCM's deterministic procedures give a unique result for a given set of inputs, while stochastic tools may give a distribution of results for a given set of inputs over a series of runs.

The deterministic procedures in the HCM give a unique value for all performance measures based on the specifics of the input data. Stochastic analysis tools apply a randomization process that might give different values for performance measures each time the process is repeated. In other words, simulation tools produce a distribution of values for each performance measure, much as would be expected from a series of repeated field studies. In supporting decision making, the distribution of values must be represented in terms of a single value, except in cases where the analysis focuses specifically on variability of the performance measures.

A comprehensive tutorial on the stochastic aspects of simulation is presented elsewhere (*14*). Topics covered include confidence intervals, the number of runs required to achieve a specified level of confidence, and hypothesis testing for comparing alternative configurations and strategies. The tutorial material is not repeated here, but it should be understood by analysts who are using simulation to produce performance measures that are comparable with those of the HCM.

Simulation modeling is based on internally generated random numbers that are controlled by specifying an initial random number or "seed" to start the generation process. In some cases, multiple seeds are used to control different aspects of the randomization. For example, driver characteristics and vehicle characteristics might be seeded differently. Multiple runs using a simulation tool with the same input data and same random number seed(s) will produce the same answers. To establish a range of answers, repetitions must be created by running a simulation tool with the same input data but different random number seed(s). Most simulation tools provide guidance on selecting random number seeds.

Number of Required Repetitions

The result of a set of simulation runs is normally represented by a summary of the average values of the performance measures of interest. Confidence in the results is influenced by the number of runs included in the set. The question raised here is, "How many runs are needed?" The answer depends on three parameters:

1. The maximum error that can be tolerated in the results: The tolerable error may be expressed in terms of an absolute value (e.g., 5 s of delay) or as a percentage of deviation from the true mean value. Greater acceptable maximum error (tolerance) suggests the need for fewer runs.
2. The degree of confidence that the true mean falls within the specified error limits: A greater degree of confidence (e.g., 99% as opposed to 95%) suggests a need for more runs.
3. The variability across simulation runs given by the standard deviation: A greater variability (higher standard deviation) suggests a need for more runs, if the other two parameters stay fixed.

In accordance with a basic statistical approach, the standard error of the mean may be estimated from the simple relationship in Equation 7-2:

Equation 7-2

$$E = \frac{s}{\sqrt{n}}$$

where

E = standard error of the mean,

s = standard deviation of the set of runs for a particular performance measure, and

n = number of runs included in the set.

The confidence limits are expressed in terms of the number of standard errors from the mean value. A target of 95% confidence is often used for this purpose. The 95% confidence interval is represented by the mean value ±1.96 standard errors.

Given the sample standard deviation s, the sample size required to produce 95% confidence of achieving a maximum tolerable error E_T can be calculated from the above relationship by using Equation 7-3:

Equation 7-3

$$n = (1.96s)^2/(E_T)^2$$

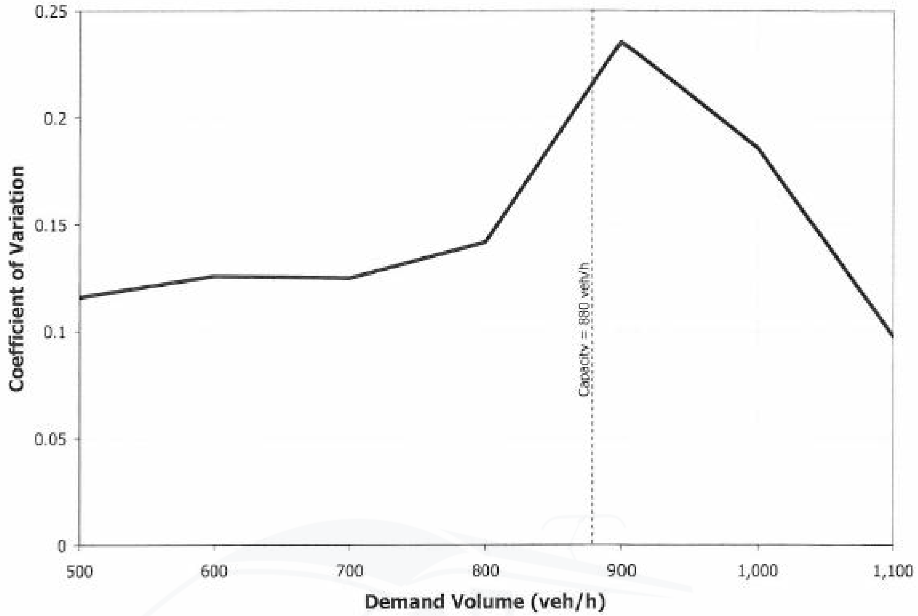
A few statistically oriented sites on the Internet offer online calculators for determining required sample sizes.

Expected Variation Between Runs

The amount of variation that will result from a set of runs given the input data is difficult to anticipate. The standard deviation of a given performance measure is best determined by making a set of test runs and applying the sample size calculations. One factor that influences the variability at signalized intersections is the degree of saturation on each approach. This influence is illustrated in Exhibit 7-9, which shows the coefficient of variation (standard deviation/mean) on a simple signalized approach as a function of the approach volume. The data for this example included 30 runs for a 15-min period.

Other factors that influence the variation in performance measure results include the length of the simulation runs and the length of the simulation warm-up periods.

Exhibit 7-9
Effect of Demand Volume on Variability of Simulated Delay on an Approach to a Signalized Intersection



At low volumes, the variability is low, with the standard deviations approaching 10% of the mean value. The variability peaks at the capacity of the approach at a value near 25%. The variability is highest at capacity because some runs will see more undersaturated cycles in the operation, while others will see more oversaturated cycles. As demand volume increases well beyond approach capacity, the variability decreases significantly as deterministic phenomena begin to govern the operation.

Exhibit 7-9 shows the relationship for a single approach to an intersection. Variability may also be expected to decrease in larger systems, as illustrated in Exhibit 7-10. This example shows a very large system with 472 links, obtained from the sample data distributed with one simulation tool. The data set included 20 runs covering a 15-min period. The performance measures cover the entire system, and the resulting variation is substantially lower than would be expected on a single approach.

Exhibit 7-10
Variability of Overall Performance Measures for a Large Urban Network

Statistic	Vehicle Miles Traveled	Vehicle Hours Delay	Vehicle Hours Total	Minutes per Mile Delay	Minutes per Mile Total	Average Speed (mi/h)
Mean	19,467	238	761	0.734	2.347	25.571
Standard deviation	140	7	9	0.019	0.021	0.218
CV	0.007	0.028	0.012	0.026	0.009	0.009
Standard error	31	1.49	1.96	0.00	0.00	0.05
Upper 95%	19,528	240.497	765.197	0.742	2.356	25.667
Lower 95%	19,406	234.661	757.508	0.725	2.337	25.475

Note: CV = coefficient of variation.

COMPARING HCM ANALYSIS RESULTS WITH ALTERNATIVE TOOLS

Alternative traffic analysis tools have been used for many years, and not all their applications have a strong requirement for HCM compatibility. The guidance presented in this chapter and in the Volume 2 and 3 chapters is addressed specifically to analysts who are seeking some degree of compatibility with the HCM procedures through the use of alternative tools. It is not the intent of the HCM to duplicate the tutorials and other authoritative documents in the literature dealing with the general application of traffic analysis tools (e.g., *15*).

Full numerical compatibility between the HCM and simulation-based analyses is seldom attainable because of differences in definitions, modeling approaches, and computational methodologies. An earlier section of this chapter dealt with the use of vehicle trajectory analysis to promote consistent definitions and computational procedures for the most important performance measures. The guidance in this section covers the following areas:

Full numerical compatibility between the HCM and alternative tools is seldom attainable because of differences in definitions, modeling approaches, and computational methodologies.

- Recognizing situations in which alternative tools should be applied,
- Recognizing situations in which basic incompatibilities preclude direct comparisons between the HCM and simulation results, and
- Achieving maximum compatibility between the HCM procedures and those of alternative tools.

Conceptual Differences Between Modeling Approaches

The analysis procedures described in the HCM are based on deterministic models that are well founded in theory and field observations. They are implemented in the form of equations that describe the behavior of traffic. Most of the equations include empirical calibration factors derived from research. Simulation modeling, on the other hand, is based on the propagation of fictitious vehicles along a roadway segment in accordance with principles of physics, rules of the road, and driver behavior. While both modeling approaches attempt to replicate phenomena that can be observed and quantified in the field, results that are mutually comparable are sometimes difficult to obtain. The conceptual differences that preclude comparison are discussed in the procedural chapters. A summary of key differences is presented here:

- Delays reported by the HCM's interrupted-flow analysis procedures apply to all the vehicles that arrive during the analysis period. When demand volumes exceed capacity, the delay to vehicles entering the system during a given period and leaving during a subsequent period are included. Delays reported by simulation are those experienced within the analysis period regardless of when vehicles entered or left the system. This concept is explored in more detail later in this chapter in the discussion of multiperiod operation.
- Densities are reported by the HCM's uninterrupted-flow chapters in terms of passenger cars per mile. Passenger car equivalency (PCE) factors are used to convert heavy vehicles to passenger cars such that the capacity of a mixed flow of heavy and light vehicles is equivalent to the capacity of a traffic stream consisting entirely of passenger cars. PCEs are applied before the density computations. Densities reported by simulation are

generally expressed in actual vehicles per mile. The effect of heavy vehicles is an implicit result of their different characteristics. Because of this difference, application of PCE factors in reverse to the computational results is difficult.

- HCM procedures deal with peak 15-min-period demand flow rates, sometimes determined by applying a PHF to hourly volumes. Simulation models do not normally apply a PHF to input volumes. Therefore, care must be taken to ensure that the demand and time periods are represented appropriately so that the analysis results are comparable.
- The HCM's urban street analysis procedures focus on performance measures for arterial through vehicles. Simulation tools generally consider all vehicles, including turning movements on a street segment. To obtain comparable results from simulation, the through movements must be isolated.
- The HCM's ramp merge and diverge procedures focus on traffic density within the influence of the merge area (usually the ramp and the two adjacent lanes). To obtain comparable results from simulation, the merge area must be defined as a separate segment for analysis and the movements in the adjacent lanes must be isolated.
- HCM procedures typically do not consider the effect of self-aggravating phenomena on the performance of a segment. For example, when traffic in a left-turn bay spills over into the adjacent through lane, the effect on the through lane performance is not considered. The inability of drivers to access their desired lane when queues back up from a downstream facility is not taken into consideration.
- Random arrivals in the traffic stream are also treated differently by the two modeling approaches. The HCM's interrupted-flow procedures apply analytical correction factors to account for this effect, while simulation modeling treats randomness explicitly by generating vehicle arrivals from statistical distributions. The difference between the two treatments affects the comparability of results.
- Some simulation tools either require or have the option of entering the origin–destination matrix instead of link and turning movement volumes. In these cases, the link and turning movement volumes are outputs from the dynamic traffic assignment models implemented as parts of the tools. HCM procedures require the link or turning movement counts as inputs.

Framework for Comparison of Performance Measures

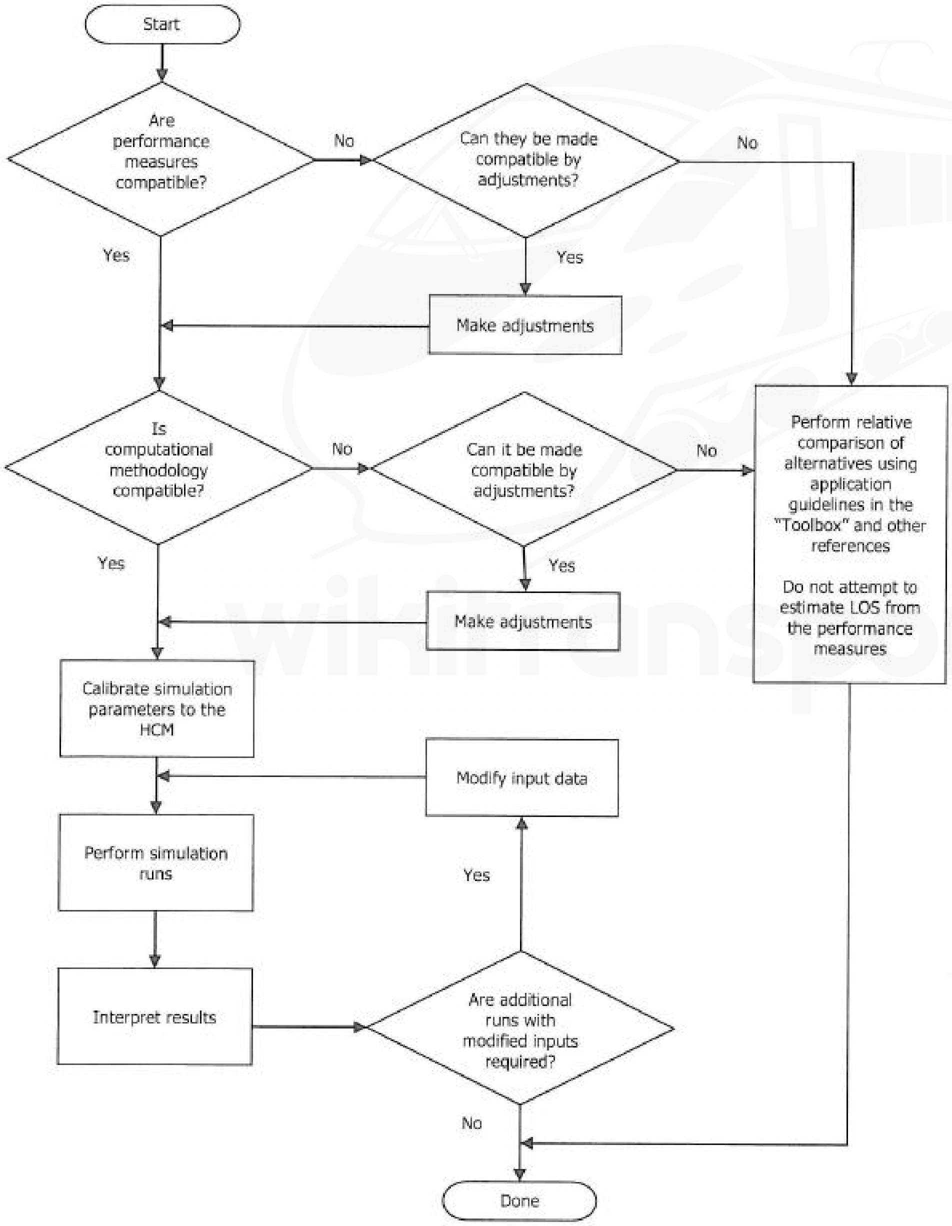
The application framework for alternative tools is presented in the form of a flowchart in Exhibit 7-11. This framework applies to all the procedural chapters in Volumes 2 and 3.

The first steps in this flowchart deal with identifying whether the situation will support analyses in which some degree of compatibility between the HCM and alternative tools may be achieved. If it is determined that, because of conceptual differences in definitions and modeling, no potential for compatibility exists, the use of alternative tools should be limited to feasibility assessment and comparison of candidate solutions. In most cases, areas of compatibility are anticipated.

The next steps cover the conduct of simulation analyses to achieve the desired level of compatibility with the HCM. Four steps are involved:

1. Calibrate the simulation parameters to the HCM, usually by seeking equal capacities from the two processes.
2. Perform a statistically appropriate number of simulation runs.
3. Interpret the results.
4. Make iterative adjustments to calibration parameters to reconcile differences.

Exhibit 7-11
Application Framework for Alternative Tools



LOS Comparisons

LOS estimates are determined by applying thresholds to specified performance measures (i.e., service measures). When LOS is estimated from performance measures obtained from an alternative tool, the performance measure must be determined in the same way the HCM determines the same measure. Alternative methods may be used to estimate and compare performance measures, as long as they are both trying to estimate the same fundamental measurement. Alternative tools that report a performance measure with the same name as an HCM measure, but with a different method of computation, should not be used to estimate LOS for HCM purposes.

Alternative tools that report a performance measure with the same name as an HCM service measure, but with a different method of computation, should not be used to estimate LOS for HCM purposes.

At present, simulation tools do not generally report performance measures by using the definitions and trajectory-based method of estimation suggested in this chapter and in Chapter 36, Concepts: Supplemental. Some refinement in the alternative tool definitions and methods of estimation based on vehicle trajectory analysis is required before valid comparisons can be made. The value of simulation modeling as a useful decision support tool is recognized, but the validity of direct comparison with performance measures defined by the HCM is questionable unless the definitions and computational procedures conform to those prescribed in this chapter.

HCM LOS thresholds are often based on service measures representing the peak 15 min of demand (arriving vehicles) rather than the 15-min period when the measure reached its maximum value.

In addition, the HCM applies LOS thresholds to performance measures that represent the peak 15 min of demand (i.e., arriving vehicles) and not necessarily the 15-min period when the performance measure produced its maximum value.

The presence of significant queues at the end of an analysis period can often be taken as an indicator that LOS F has been reached.

One consideration that makes simulation more compatible with the HCM in reporting LOS is the criterion that, for most roadway segments, LOS F is assigned to any segment that operates above its capacity. Therefore, without the need for a detailed trajectory analysis, the presence of significant queues at the end of the analysis period can be taken as an indicator that LOS F has been reached in the segment. When queues extend into a given segment from a downstream bottleneck, the analysis procedures for freeway facilities described in Chapter 10 instead of the procedures for individual segments described in Chapters 12 to 14 should be used. On the other hand, when the purpose of the analysis is to develop a facility design that will produce a LOS better than F, the analyst must ensure that the performance measure on which LOS is based is estimated in a manner compatible with the HCM.

Estimation of Capacity by Simulation

The capacity of an approach or segment is often estimated by overloading it and observing the maximum throughput. This technique is valid in some cases, but it must be used with caution when congestion could become a self-aggravating phenomenon. For example, when lane selection is important (as in the case of a turning bay) and congestion keeps vehicles from their desired lane, the throughput can drop below its theoretical maximum. This phenomenon is not recognized by most of the HCM's deterministic analysis procedures. Therefore, if the objective is to seek HCM-compatible capacity levels, the approach or segment should not be overloaded by more than a few percent. In this case, the process of determining capacity might require iteration. On the other hand, if the objective is to evaluate the operation under an anticipated heavy overload, simulation modeling might provide some insight into the nature of the resulting congestion. In that case, the analysis could require development of the relationship between demand and throughput. Examples of the adverse effects of heavy overloading are presented in Chapter 27, Freeway Weaving: Supplemental, and Chapter 34, Interchange Ramp Terminals: Supplemental.

Temporal and Spatial Boundaries

The LOS reported by the HCM procedures applies to the 15-min period with the maximum number of arrivals (i.e., entering vehicles). This period might not be the same one that reports the maximum delay because of residual queues. In a discussion of the limitations of performance measure estimation and use (*15*), there is frequent reference to the issues that arise in the treatment of incomplete trips within the analysis period, including those that entered the special domain of the analysis but did not exit during the analysis period and those that were unable to enter the spatial domain because of queue backup. The main problem lies in differences in treatment among different models.

Complete Versus Incomplete Trips

Definition of incomplete trips within the temporal and spatial boundaries of an analysis.

Five categories are proposed with respect to incomplete trips (*15*):

1. Vehicles that were present at the start of the analysis period and were able to exit the system successfully before the end of the analysis period;
2. Vehicles that were present at the start of the analysis period but were unable to exit the system successfully before the end of the analysis period;
3. Vehicles that were able to enter the system during the analysis period but were unable to exit the system successfully before the end of the analysis period;
4. Vehicles that tried to enter the system during the analysis period but were unsuccessful; and
5. Vehicles that entered during the analysis period and were able to exit the system successfully before the end of the analysis period.

All categories except the fifth represent incomplete trips. It is suggested elsewhere (*15*) that, if a specific analysis contains more than 5% incomplete trips, the period length should be increased.

Differences between the objectives of the Federal Highway Administration's *Traffic Analysis Toolbox* (*16*) and those of the HCM should be recognized. The purpose of the *Toolbox* is to provide general guidance on applying traffic analysis tools. The guidance on simulation included in this chapter is more focused on developing HCM-compatible performance measures so that those measures can be used in conjunction with the HCM procedures. Therefore, this discussion must examine temporal and spatial boundaries from the same perspective as the HCM procedures.

When undersaturated operation is being studied, the definition of the facility in time and space is much less important. The operation tends to be more homogeneous when d/c ratios are less than 1.00. Extending the analysis period will give a larger sample of vehicles for most performance measures but will not affect the measures significantly.

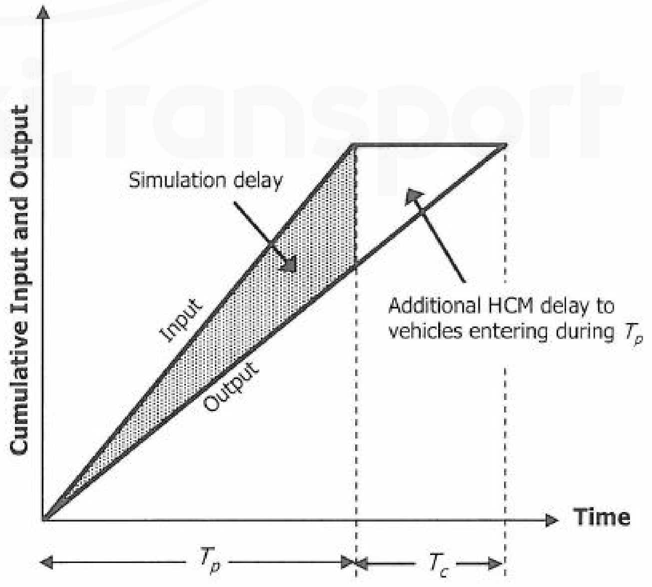
The issues are more conspicuous when the *d/c* ratio is greater than 1.00 for short periods. In this case, queues build up and the analysis (either HCM or simulation) must define temporal boundaries that begin and end without congestion. It is also desirable, but not essential, that the spatial boundaries encompass uncongested operation. Failure to define a spatially adequate system will result in vehicles being denied entry, but these vehicles will eventually be processed if the analysis period is long enough.

Delay on Oversaturated Signalized Approaches

LOS for interrupted flow is defined by the HCM in terms of the delay to all vehicles *entering* the facility during the analysis period. All vehicles wishing to enter are assumed to enter. Those unable to exit from a signalized intersection are accumulated in a residual queue and are assumed to exit later. The incremental (d_2) term of the delay model accounts for delay to vehicles that exit in a later period. The d_3 term accounts for the additional delay caused by an initial queue.

The formulation illustrated in Exhibit 7-12 recognizes that delay accrues when the vehicular input to a system exceeds the output for a period of time. The HCM uses this formulation to estimate delay that accrues at a signalized intersection when volume exceeds capacity over the analysis time period, T_p. The HCM delay in Exhibit 7-12 is represented by the area of the two triangles shown in the figure. The area within the two triangles is referred to as the *deterministic queue delay* (DQD). The DQD may be determined as $5 \times T_p \times (X - 1)$, where X is the *d/c* ratio.

Exhibit 7-12
Oversaturated Delay Representation by the HCM and Simulation Modeling



When demand exceeds capacity, some vehicles that arrive during T_p will depart during the next period. The time required to clear all vehicles arriving during T_p is shown above as T_c. Because the HCM defines delay in terms of the delay experienced by *all vehicles that arrive* during the analysis period, the delay computations must include the delay to those vehicles that arrive during T_p and depart during T_c.

The HCM defines delay in terms of the delay experienced by all vehicles arriving during an analysis period (e.g., 15 min), including delay accumulated after the end of the analysis period.

This definition differs from the delay definition used by most simulation tools, which address the delay experienced *during* the analysis period. The HCM definition includes the area within both triangles of Exhibit 7-12. The simulation definition includes only that portion of the area within the interval T_p.

Most simulation tools define delay in terms of the delay experienced by all vehicles during a specified analysis period and do not include delay from later time periods.

Compatibility with the HCM definition dictates that a control delay measure should be based on all entering vehicles, without regard to completed trips. An adequate initialization period should be used to load the facility. When the *d/c* ratio is less than 1.00, some vehicles that entered before the start of the analysis (i.e., during the initialization period) will exit the system. There will also be vehicles that enter the system late in the period and do not exit. Including these incomplete trips will not bias the delay results.

When demand exceeds capacity for a single period, the HCM delay formulation shown in Exhibit 7-12 will include the delay to vehicles that exit in the next period. The simulation results will not. To produce a simulation run that replicates the HCM single-period calculations, a second period with zero demand must be added to the simulation run. Only the vehicles that were unable to exit during the first period will be accommodated during the second period. The sum of the delays for both periods will be equivalent to the HCM delay shown in Exhibit 7-12.

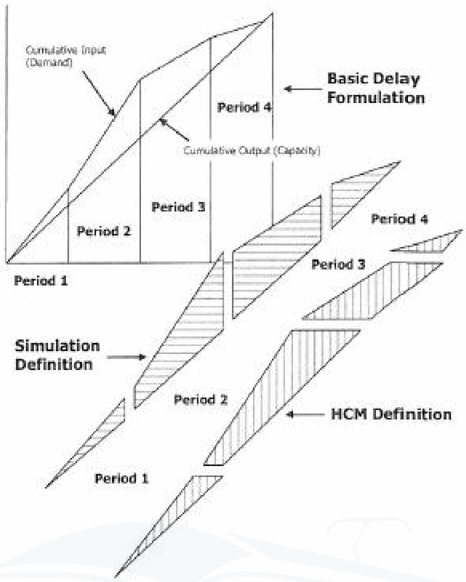
Delay for Multiperiod Oversaturation

When the operation is oversaturated beyond a single period, a multiperiod analysis ensuring that the duration is sufficient to encompass congestion-free conditions at both ends is necessary.

When operations are oversaturated beyond a single analysis period, a multiperiod analysis is necessary.

As an example, HCM and simulation delay formulations are illustrated in Exhibit 7-13, which depicts the analysis of four consecutive periods that begin and end without congestion. The analysis is performed sequentially, with the residual queues from one period applied as initial queues to the next period. The first two periods have demand in excess of capacity. In the last two periods, the demand drops sufficiently below capacity to allow the queues to clear. Delay polygons are shown for the HCM and simulation definitions for all periods. The shape of the delay polygons differs in the two formulations, so the delay values are not the same for any period. The important thing is that the sum of the areas for the four polygons is the same for each definition.

Exhibit 7-13
Comparison of HCM and Simulation Delay Definitions for Four Oversaturated Periods



Therefore, to promote compatibility between the HCM and simulation delay definitions for a multiperiod analysis involving oversaturated signalized approaches, the simulation results should be obtained as follows:

- Ensure that the analysis period is long enough to encompass a period of congestion-free operation at both ends.
- Perform an adequate initialization to load the system.
- Perform the analysis on all vehicles entering the system during each period.
- Do not ignore any entering or exiting vehicle in any period; otherwise, the results could be biased.
- If a measure of delay per vehicle is desired, develop the total delay by summing the delays for the individual periods and divide that delay by the total entering volume.

Delay is not reported explicitly in the freeway segment chapters (Chapters 12 to 14). However, delay may be inferred from each chapter's free-flow and average speed computations. This step is performed in Chapter 10 for analysis of freeway facilities involving a combination of different segment types. The delay due to queues forming from bottlenecks is added to the individual segment delays. While the delay computations are conceptually simpler for freeways, the same guidance for developing compatible simulation results applies to other system elements.

Density is defined only in the uninterrupted-flow chapters. Unlike delay measures, which apply to individual vehicles, the density measure applies to the facility. Therefore, the issue of how to treat incomplete trips does not apply. Instantaneous densities should be determined from simulation by time step and should be aggregated over suitable intervals. The average density over a long period will be of less interest for most purposes than the variation of density that takes place in time and space. Typical aggregation intervals for that purpose will range from 5 to 15 min.

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