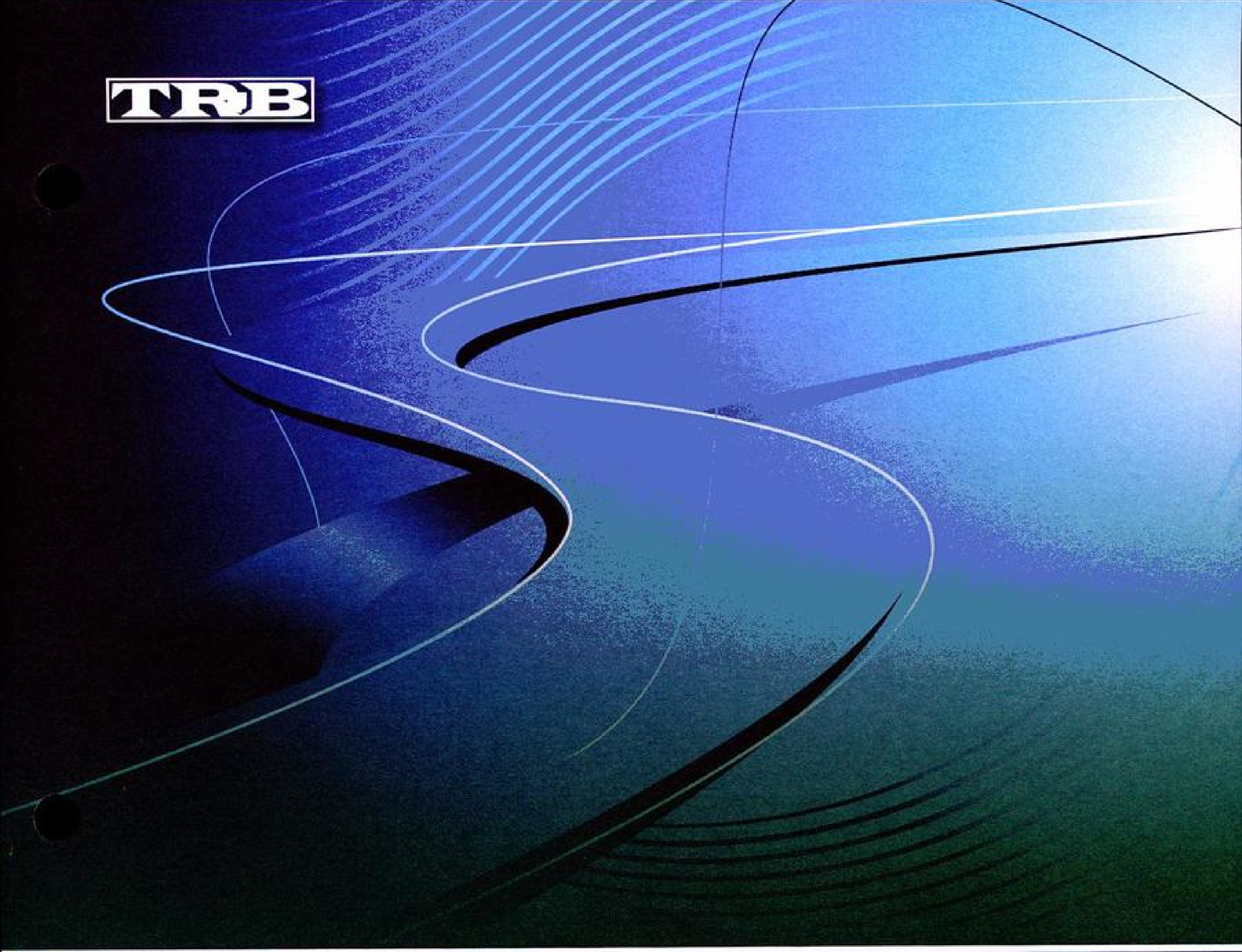

HIGHWAY CAPACITY MANUAL

6TH EDITION | A GUIDE FOR MULTIMODAL MOBILITY ANALYSIS

VOLUME 1: CONCEPTS

The National Academies of
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FOREWORD

For more than 60 years, the *Highway Capacity Manual* (HCM) has presented tools for quickly evaluating and comparing the operational effects of alternative design scenarios, allowing analysts to screen a variety of approaches and select a reasonable number before considering more costly measures. The HCM has evolved significantly, with each edition addressing the contemporary needs of transportation professionals and society.

This new edition of the HCM adds a subtitle: *A Guide for Multimodal Mobility Analysis*. This underscores the HCM's focus on evaluating the operational performance of several modes, including pedestrians and bicycles, and their interactions. It is called the *6th Edition*, with no year attached, and each chapter indicates a version number, to allow for updates.

This edition provides the following pertinent tools:

- Analysis methodologies for evaluating **travel time reliability**. These new tools consider the distribution of travel times over a long period (for example, an entire year), instead of evaluating a single analysis period, as was done in previous editions of the HCM.
- Tools for analyzing the operational effects of **active traffic and demand management**. Strategies include managed lane facilities and freeway management policies.
- Enhanced methods for analyzing **pedestrian, bicycle, and transit facilities, as well as their interactions with motor vehicles**.
- New tools for the analysis of **alternative interchanges and intersections**, such as diverging diamond interchanges and restricted crossing U-turn intersections.
- Guidance on the **use of simulation and other tools** in conjunction with HCM analyses. The HCM discusses specific cases that may require alternative tools and simulation and explains how these can assist in providing performance measures not available from HCM methods or in analyzing highway designs not addressed within the HCM's performance measurement framework.

Although this edition of the HCM registers many firsts (which are identified in Chapter 1), it continues to build on the significant contributions of many dedicated experts in the field.[1]

The first HCM was published in 1950 as a joint venture of the Highway Research Board's Committee on Highway Capacity and the Bureau of Public Roads. O. K. Normann, committee chair, and William Walker, committee secretary, led that effort. The manual was the first international document on the broad subject of capacity and provided definitions of key terms, a compilation of maximum observed flows, and the initial fundamentals of capacity.

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[1] Thanks are extended to Adolf D. May for this short history of the *Highway Capacity Manual*, which was first provided in his Foreword to the 1994 edition.

The second edition was published in 1965 by the Highway Research Board and authored by the Committee on Highway Capacity. O. K. Normann led much of this effort until his untimely death in 1964. Carl C. Saal continued the work as the new committee chair with Arthur A. Carter, Jr., as secretary. The Bureau of Public Roads was again a significant contributor to the project. The 1965 manual was a significant extension of the 1950 edition and introduced the concept of level of service.

The third edition of the manual was published in 1985 by the Transportation Research Board (TRB) and authored by the Committee on Highway Capacity and Quality of Service, chaired by Carlton C. Robinson, with Charles W. Dale as secretary. Credit is also due to Robert C. Blumenthal and James H. Kell, who served as committee chairs between the publication of the 1965 and 1985 editions. The 1985 edition extended capacity analysis to additional facility types, incorporated driver perceptions into level of service, and was the first to have the analysis procedures implemented in computer software.

An update to the third edition of the manual was published in 1994 with Adolf D. May as chair of the committee and Wayne K. Kittelson as secretary. The 1994 edition of the manual is noted for new procedures for the analysis of freeway ramp junctions, all-way and two-way STOP-controlled intersections, and two-lane rural highways.

The fourth edition of the manual was published in 2000 with John D. Zegeer as chair of the committee and Richard G. Dowling as secretary. That manual was the first to test novel electronic formats for the manual using hyperlinked text and narrated self-guided tutorials for some of the example problems.

The fifth edition was published in 2010 with Richard G. Dowling as chair and Lily Elefteriadou as secretary. It was the first edition to include a multimodal analysis framework and the first to discuss the proper application of simulation along with the HCM methods. In addition, it was the first to involve a range of volunteers from outside the Committee on Highway Capacity and Quality of Service (HCQS), including representatives from other TRB committees, as well as transportation professionals affiliated with the Institute of Transportation Engineers (ITE).

The methods included in this sixth edition were evaluated by approximately 200 reviewers, who provided a total of 3,331 comments on the draft materials. The HCQS Committee members thank all volunteers who contributed to the development of this edition. We are also grateful for the support we have received from the members and staff of ITE. Our joint summer meetings with local ITE sections throughout the production of the manual were particularly informative and productive.

Throughout this effort, the advice and support of Richard Cunard, TRB's Engineer of Traffic and Operations, was extremely valuable in helping the committee anticipate, address, and overcome the obstacles that arise whenever a major new document is published.

The sixth edition of the HCM would never have become a reality without the financial and administrative support of the Federal Highway Administration, the second Strategic Highway Research Program, and the National Cooperative Highway Research Program (NCHRP). This edition was funded through NCHRP Project 03-115, and was monitored by a panel chaired by Robert Bryson, with Ray Derr as Senior Program Officer. The committee thanks the NCHRP 03-115 panel, its staff, and its contractor, Kittelson & Associates, Inc., for delivering a high-quality manual that addresses the current needs of the transportation engineering and planning community.

The committee invites those interested in improving the profession's understanding of capacity and quality of service analysis to contact us via the links at https://sites.google.com/site/ahb40hcqs/home and to become involved.

For the Standing Committee on Highway Capacity and Quality of Service (AHB40),

Lily Elefteriadou
Committee Chair
March 1, 2016

F. Thomas Creasey
Committee Secretary

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The *Highway Capacity Manual* is the result of the coordinated efforts of many individuals, groups, research organizations, and government agencies. The TRB Committee on Highway Capacity and Quality of Service is responsible for the content of the *Highway Capacity Manual*; preparation of the manual was accomplished through the efforts of the following groups and individuals:

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This project developed Chapters 23 and 34 on alternative intersections and interchange ramp terminals outside the main NCHRP Project 03-115 production contract. Chapter 1, HCM User's Guide, lists other Cooperative Research Program, Federal Highway Administration, and Second Strategic Highway Research Program projects that also contributed significantly to this edition of the HCM.

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CHAPTER 1
HCM USER'S GUIDE

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

OVERVIEW

The *Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis* (HCM) continues the manual's evolution from its original objective—providing methods for quantifying highway capacity. In its current form, it serves as a fundamental reference on concepts, performance measures, and analysis techniques for evaluating the multimodal operation of streets, highways, freeways, and off-street pathways. The Sixth Edition incorporates the latest research on highway capacity, quality of service, and travel time reliability and improves the HCM's chapter outlines. The objective is to help practitioners applying HCM methods understand their basic concepts, computational steps, and outputs. These changes are designed to keep the manual in step with its users' needs and present times.

The 1950 HCM (*1*) was the first document to quantify the concept of capacity for transportation facilities and focused almost entirely on that subject. This focus was in response to the rapid expansion of the U.S. roadway system after World War II and the need to determine lane requirements for the Interstate highway system and the roads that provided access to it. The manual was designed to be "a practical guide by which the engineer, having determined the essential facts, can design a new highway or revamp an old one with assurance that the resulting capacity will be as calculated."

The focus on design continued in the 1965 HCM (*2*), but the level-of-service (LOS) concept was also introduced with this edition, along with a chapter on bus transit. The HCM permitted the "determination of the capacity, service volume, or level of service which will be provided by either a new highway design, or an existing highway under specified conditions."

The 1985 HCM (*3*) was another significant step in the evolution of the HCM. It refined the concept of LOS and incorporated the results of several major research projects performed since the publication of the 1965 HCM. The target audience was broadened through the addition of chapters on pedestrians and bicycles and an expansion of the transit chapter.

A substantial increase in the volume and breadth of material occurred with the publication of the HCM2000 (*4*). The intent of the manual was "to provide a systematic and consistent basis for assessing the capacity and level of service for elements of the surface transportation system and also for systems that involve a series or a combination of individual facilities."

The HCM 2010 (*5*) added much new material from research projects completed after the publication of the HCM2000 and was reorganized to make its contents more accessible and understandable. That edition also promoted the consideration of all roadway users and the use of a broader range of performance measures in the assessment of transportation facility performance.

New topics addressed by this Sixth Edition include travel time reliability and the operation of managed lanes, work zones, and alternative intersections.

This Sixth Edition of the HCM incorporates research to update older HCM content and research on a number of topics new to the HCM, including travel time reliability and managed (e.g., high-occupancy vehicle) lane, work zone, and alternative intersection (e.g., displaced left turn) operations.

As the preceding discussion indicates, the HCM has evolved over the years to keep pace with the needs of its users and society, as the focus of surface transportation planning and operations in the United States has moved from designing and constructing the Interstate highway system to managing a complex transportation system that serves a variety of users and travel modes. Transportation agencies daily face the challenges of constrained fiscal resources and rights-of-way. They increasingly focus on designing and operating roadway facilities in the context of the surrounding land uses and the modal priorities assigned to a given facility.

Although the HCM's content has evolved, its name has stayed the same since 1950 and no longer conveys the HCM's full range of applications. Therefore, the Sixth Edition adds the subtitle "A Guide for Multimodal Mobility Analysis" to highlight to practitioners and decision makers the multimodal performance measurement tools and guidance provided by the HCM.

Mobility consists of four dimensions:
- *Quantity of travel,*
- *Quality of travel,*
- *Accessibility, and*
- *Capacity.*

Providing *mobility* for people and goods is transportation's most essential function. It consists of four dimensions:

- *Quantity of travel,* the magnitude of use of a transportation facility or service;
- *Quality of travel,* users' perceptions of travel on a transportation facility or service with respect to their expectations;
- *Accessibility,* the ease with which travelers can engage in desired activities; and
- *Capacity,* the ability of a transportation facility or service to meet the quantity of travel demanded of it.

The subtitle "A Guide for Multimodal Mobility Analysis" captures the HCM's ability to quantify roadway performance across multiple dimensions and travel modes.

The HCM historically has been the leading reference document for analyzing the mobility dimensions of quality of travel and capacity. Quantity of travel is a key input to the HCM's methods for analyzing motorized vehicle quality of travel and capacity utilization. Thus, "A Guide for Multimodal Mobility Analysis" captures the HCM's ability to quantify roadway performance across multiple dimensions and travel modes.

Finally, many previous editions of the HCM have had a year attached to them. As both the HCM's breadth and the quantity of HCM-related research have increased over time, waiting for years for a critical mass of research to accumulate before production of a new HCM edition has become impractical. This edition is simply titled the "Sixth Edition," with a version number provided for each chapter, starting with Version 6.0 for the initial publication. This approach will allow individual chapters to be updated more quickly as new research is completed, while continuing to allow practitioners to link their analysis to a particular version of an HCM methodology.

The remainder of this chapter provides a starting point for using the *Highway Capacity Manual, Sixth Edition: A Guide for Multimodal Mobility Analysis* and for learning about the changes made in this edition.

CHAPTER ORGANIZATION

Readers new to the HCM can use this chapter as a road map to all of the resources available within the printed manual and online. Experienced HCM users are encouraged to read at least Section 5, which summarizes the significant changes in the HCM that have occurred relative to the HCM 2010.

Section 2 presents the purpose, objectives, intended use, and target users of the HCM.

Section 3 describes the contents of the four printed and online volumes that make up the HCM, summarizes the additional user resources available through the online Volume 4, and discusses the relationship of commercial software that implements HCM methods to the HCM itself.

Section 4 provides guidance on applying the HCM for international users.

Section 5 lists the significant changes made in the Sixth Edition and identifies the research basis for these changes.

Section 6 describes companion documents to the HCM that address topics outside the HCM's scope and that may need to be applied during an analysis. These documents are updated on different schedules from the HCM and serve as fundamental resources for topics within their respective scopes.

RELATED HCM CONTENT

The remainder of Volume 1 presents basic capacity, quality-of-service, and analysis concepts that readers should be familiar with before they apply the HCM. Chapter 8, HCM Primer, provides an executive summary of the HCM, including its terminology, methods, and performance measures. It is written for a nontechnical audience (e.g., decision makers who may be presented with the results of HCM analyses for the purpose of establishing policy or public interest findings).

2. HCM PURPOSE AND SCOPE

PURPOSE AND OBJECTIVES

Quality of service describes how well a transportation facility or service operates from the traveler's perspective.

The purpose of the HCM is to provide methodologies and associated application procedures for evaluating the multimodal performance of highway and street facilities in terms of operational measures and one or more quality-of-service indicators.

The objectives of the HCM are to

1. Define performance measures and describe survey methods for key traffic characteristics,
2. Provide methodologies for estimating and predicting performance measures, and
3. Explain methodologies at a level of detail that allows readers to understand the factors affecting multimodal operation.

Level of service is the A–F stratification of quality of service.

The HCM presents the best available techniques at the time of publishing for determining capacity and LOS. However, it does not establish a legal standard for highway design or construction.

INTENDED USE

The HCM is intended to be used primarily for the analysis areas listed below, to the extent that they are supported by the individual analysis methodologies.

- *Levels of analysis:* operations, design, preliminary engineering, and planning.
- *Travel modes:* motorized vehicles, pedestrian, and bicycle, plus transit when it is part of a multimodal urban street facility.
- *Spatial coverage:* points, segments, and facilities.
- *Temporal coverage:* undersaturated and oversaturated conditions.

TARGET USERS

The HCM is prepared for use by (*a*) engineers who work in the field of traffic operations or highway geometric design and (*b*) transportation planners who work in the field of transportation system management. To use the manual effectively and to apply its methodologies, some technical background is desirable—typically university-level training or technical work in a public agency or consulting firm.

The HCM is also useful to management personnel, educators, air quality specialists, noise specialists, elected officials, regional land use planners, and interest groups representing special users.

3. STRUCTURE

OVERVIEW

The HCM consists of four volumes:

1. Concepts,
2. Uninterrupted Flow,
3. Interrupted Flow, and
4. Applications Guide.

Volumes 1–3 are available in the print version of the HCM; Volume 4 is only available online. The sections below describe the contents of each volume.

VOLUME 1: CONCEPTS

VOLUME 1: CONCEPTS
1. HCM User's Guide
2. Applications
3. Modal Characteristics
4. Traffic Operations and Capacity Concepts
5. Quality and Level-of-Service Concepts
6. HCM and Alternative Analysis Tools
7. Interpreting HCM and Alternative Tool Results
8. HCM Primer
9. Glossary and Symbols

Volume 1 covers the basic information that an analyst should be familiar with before performing capacity or quality-of-service analyses:

- Chapter 1, HCM User's Guide, describes the purpose, scope, structure, and research basis of the HCM.
- Chapter 2, Applications, describes the types of analysis and operating conditions to which the HCM can be applied, defines roadway system elements, and introduces the travel modes addressed by the HCM.
- Chapter 3, Modal Characteristics, discusses demand variations by mode, factors that contribute to a traveler's experience during a trip, the types of transportation facilities used by different modes, and the interactions that occur between modes.
- Chapter 4, Traffic Operations and Capacity Concepts, describes how basic traffic operations relationships, such as speed, flow, density, capacity, and travel time reliability, apply to the travel modes covered by the HCM.
- Chapter 5, Quality and Level-of-Service Concepts, presents the concepts of quality of service and LOS and summarizes the service measures used in the HCM to describe the quality of service experienced by modal travelers.
- Chapter 6, HCM and Alternative Analysis Tools, describes the types of analysis tools used by the HCM and presents the range of alternative tools that might be used to supplement HCM procedures.
- Chapter 7, Interpreting HCM and Alternative Tool Results, provides guidance on the level of precision to use during an analysis and during presentation of analysis results, as well as guidance on comparing HCM analysis results with results from alternative tools.
- Chapter 8, HCM Primer, serves as an executive summary of the HCM for decision makers.

Chapter 8, HCM Primer, serves as an executive summary of the HCM for decision makers.

- Chapter 9, Glossary and Symbols, defines the technical terms used in the HCM and presents the symbols used to represent different variables in HCM methods.

VOLUME 2: UNINTERRUPTED FLOW
10. Freeway Facilities Core Methodology
11. Freeway Reliability Analysis
12. Basic Freeway and Multilane Highway Segments
13. Freeway Weaving Segments
14. Freeway Merge and Diverge Segments
15. Two-Lane Highways

Uninterrupted-flow system elements, such as freeways, have no fixed causes of delay or interruption external to the traffic stream.

VOLUME 2: UNINTERRUPTED FLOW

Volume 2 contains the methodological chapters relating to uninterrupted-flow system elements. These elements include freeways, managed lanes, multilane highways, two-lane highways, and their components. Their key shared characteristic is that they have no fixed causes of delay or interruption external to the traffic stream.

All of the material necessary for performing an analysis of one of these system elements appears in these chapters: a description of the methodology thorough enough to allow an analyst to understand the steps involved (although not necessarily replicate them by hand), the scope and limitations of the methodology, suggested default values, LOS thresholds, and guidance on special cases and the use of alternative tools.

The following chapters are included in Volume 2:

- Chapter 10, Freeway Facilities Core Methodology, presents basic concepts related to freeways and their component elements, including managed lanes, and the methodology for evaluating the operation of an extended section of freeway. Both undersaturated (i.e., below capacity) and oversaturated (i.e., above capacity) conditions can be evaluated.

Chapter 11 was added as part of the Sixth Edition and presents methods for evaluating travel time reliability and the effects of ATDM strategies on freeways.

- Chapter 11, Freeway Reliability Analysis, describes how the Chapter 10 core methodology can be applied to evaluate the impacts of demand variation, severe weather, incidents, work zones, special events, and active traffic and demand management (ATDM) strategies on freeway operations and travel time reliability.

Because basic freeway segments and multilane highways operate similarly in many ways, they have been combined into a single chapter as part of the Sixth Edition.

- Chapter 12, Basic Freeway and Multilane Highway Segments, presents methodologies for analyzing the operations of freeway and multilane highway segments outside the influence of merging, diverging, and weaving maneuvers and (in the case of multilane highways) of signalized intersections.
- Chapter 13, Freeway Weaving Segments, presents a methodology for evaluating freeway, managed lane, collector–distributor road, and multilane highway segments where traffic entering from an on-ramp interacts with traffic desiring to exit at a nearby downstream off-ramp.
- Chapter 14, Freeway Merge and Diverge Segments, presents methodologies for evaluating roadway segments downstream of on-ramps and upstream of off-ramps, where weaving does not occur.

Chapter 15, Two-Lane Highways, provides a method for evaluating bicycle LOS on multilane and two-lane highways.

- Chapter 15, Two-Lane Highways, describes methods for analyzing the operations of various classes of two-lane highways.

VOLUME 3: INTERRUPTED FLOW

Volume 3 contains the methodological chapters relating to interrupted-flow system elements. These consist of urban streets and the intersections along them, as well as off-street pedestrian and bicycle facilities. These system elements provide traffic control devices, such as traffic signals and STOP signs, that periodically interrupt the traffic stream.

Interrupted-flow system elements, such as urban streets, have traffic control devices such as traffic signals and STOP signs that periodically interrupt the traffic stream.

Similar to Volume 2, all of the material necessary for performing an analysis of an interrupted-flow system element appears in these chapters: a description of the methodology thorough enough to allow an analyst to understand the steps involved (although not necessarily replicate them by hand), the scope and limitations of the methodology, suggested default values, LOS thresholds, and guidance on special cases and the use of alternative tools. In addition, where supported by research, analysis methods for the pedestrian and bicycle modes are incorporated into these chapters. Public transit material specific to multimodal analyses also appears in selected Volume 3 chapters; readers are referred to the *Transit Capacity and Quality of Service Manual* (TCQSM) (*6*) for transit-specific analysis procedures.

Analysis methods for the pedestrian, bicycle, and transit modes are provided in Chapters 16 and 18 and selected other Volume 3 chapters.

The following chapters are included in Volume 3:

- Chapter 16, Urban Street Facilities, presents methods for evaluating the operation of motorized vehicles, bicyclists, pedestrians, and transit vehicles (and their passengers) along an extended section of an urban street.
- Chapter 17, Urban Street Reliability and ATDM, describes how Chapter 16's facility methodology can be applied to evaluate the impacts of demand variation, severe weather, incidents, work zones, special events, and ATDM strategies on urban street operations and travel time reliability.

Chapter 17 was added to the Sixth Edition and presents methods for evaluating travel time reliability and the effects of ATDM strategies on urban streets.

- Chapter 18, Urban Street Segments, presents methods for evaluating the operations of the various travel modes along an urban street segment bounded by signalized intersections or other forms of traffic control that may require the street's traffic to stop.
- Chapters 19 through 22 provide methods for evaluating motorized vehicle operations at signalized intersections, two-way STOP-controlled (TWSC) intersections, all-way STOP-controlled (AWSC) intersections, and roundabouts, respectively. Some of these intersection-specific chapters also provide analysis guidance for the pedestrian or bicycle modes.
- Chapter 23, Ramp Terminals and Alternative Intersections, describes methods for analyzing closely spaced intersections, including interchange ramp terminals and alternative intersection forms (e.g., displaced left-turn intersections) comprising multiple junctions.

The alternative intersection and interchange material in Chapter 23 is new in the Sixth Edition.

- Chapter 24, Off-Street Pedestrian and Bicycle Facilities, provides methods for evaluating the operation of off-street walkways, stairways, shared-use paths, and exclusive bicycle paths from the perspectives of the pedestrian or bicycle modes, as appropriate.

VOLUME 4: APPLICATIONS GUIDE

Volume 4 is an online-only volume accessible at hcm.trb.org. It serves as a resource to the HCM community by providing the following:

- *Supplemental chapters* containing example problems demonstrating the use of HCM methods, along with details of the more computationally complex HCM methodologies;
- *Interpretations* of HCM methods provided by the Transportation Research Board (TRB) Committee on Highway Capacity and Quality of Service;
- *Errata*;
- A *technical reference library* providing access to much of the original research forming the basis of HCM methods;
- *Applications guides* demonstrating the process of applying HCM methods to the variety of operations (*7, 8*) and planning and preliminary engineering projects (*9*) that HCM users may work on; and
- A *discussion forum* that allows HCM users to pose questions and receive answers from other HCM users.

Emerging topics chapters may be added to Volume 4 in the future, as research develops new HCM material that the TRB Committee on Highway Capacity and Quality of Service chooses to adopt immediately, before the next HCM edition. This approach reduces the time between the completion of research and the adoption of research results and their consideration as official HCM methods. For example, three emerging topics chapters on travel time reliability and managed lanes were adopted after the original publication of the HCM 2010; that material has now been incorporated into Volume 2 and 3 chapters as part of the Sixth Edition.

Access Volume 4 at hcm.trb.org.

Volume 4 is open to all but requires a free, one-time registration for access to its content. As part of the registration process, users can choose to be notified by e-mail (typically once or twice a year) when new material is added to Volume 4.

COMPUTATIONAL ENGINES

HCM chapters describe, at a minimum, the process used by a given methodology. For simpler methodologies, the chapters fully describe the computational steps involved.

Supplemental chapters in Volume 4 provide calculation details for the more computationally complex methods.

Computational engines document all the calculation steps for the most complex methods, such as those involving iterative calculations.

Historically, all HCM methodologies have been fully documented within the manual through text, figures, and worksheets (the Freeway Facilities chapter in the HCM2000 represented the first departure from this pattern). However, in response to practitioner needs and identified HCM limitations, methodologies have continued to grow in complexity, and some have reached the point where they can no longer be feasibly documented in such a manner (for example, methodologies that require multiple iterations to reach a solution). In these cases, computational engines become an important means by which details of some of the more complex calculations can be described fully. For the most complex methodologies, the respective Volume 2 or 3 chapter, the related Volume 4 supplemental chapter, and the computational engine together provide the most efficient and effective way of fully documenting the methodology.

The TRB Committee on Highway Capacity and Quality of Service maintains computational engines for most HCM methodologies for evaluating methodologies as they are developed, developing new example problems, identifying needed improvements, and judging the impact of proposed changes. These engines are "research-grade" software tools for developing and documenting HCM methodologies and do not have or need the sophisticated interfaces and input data manipulation techniques that would make them suitable for use in an engineering or planning office.

Unless specifically noted otherwise in a particular HCM chapter, computational engines are not publicly distributed but are made available on request to researchers, practitioners, software developers, students, and others who are interested in understanding the inner workings of a particular HCM methodology. Engines that are publicly distributed are provided in the Technical Reference Library section of online Volume 4. All computational engines are provided as is; neither TRB nor its Committee on Highway Capacity and Quality of Service provides support for them.

COMMERCIAL SOFTWARE

To assist users in implementing the methodologies in the manual, commercial software is available (and has been since the publication of the 1985 HCM) to perform the numerical calculations for the more computationally intensive methods. A variety of commercial software products are available that implement HCM techniques and provide sophisticated user interfaces and data manipulation tools. TRB does not review or endorse commercial products.

4. INTERNATIONAL USE

APPLICATIONS

Capacity and quality-of-service analyses have generated interest on an international scale. The HCM has been translated into several languages, and research conducted in numerous countries outside of North America has contributed to the development of HCM methodologies. However, HCM users are cautioned that most of the research base, the default values, and the typical applications are from North America, particularly from the United States. Although there is considerable value in the general methods presented, their use outside of North America requires an emphasis on calibration of the equations and procedures to local conditions and on recognition of major differences in the composition of traffic; in driver, pedestrian, and bicycle characteristics; and in typical geometrics and control measures.

METRIC CONVERSION GUIDE

The HCM2000 (*4*) was produced as two editions, one using U.S. customary units and the other using metric units. At that time, U.S. states were moving toward compliance with federal requirements to use metric units in the design of roadways. As a result, the HCM2000 was published in "U.S. customary" and "metric" versions. Because the federal metrication requirements were later dropped and most states returned to U.S. customary units, subsequent HCM editions have only used U.S. customary units. To assist international users, Exhibit 1-1 provides approximate conversion factors from U.S. customary to metric units.

Exhibit 1-1
Metric Conversion Table

Symbol	When You Know	Multiply By	To Find	Symbol
		Length		
in.	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		Area		
in.^{2}	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		Volume		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		Mass		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2,000 lb)	0.907	megagrams (or metric tons)	Mg (or t)
		Temperature (exact conversion)		
°F	Fahrenheit	(F – 32)/1.8	Celsius	°C
		Force and Pressure or Stress		
lbf	pound force	4.45	newtons	N
lbf/in.^{2}	pound force per square inch	6.89	kilopascals	kPa

Source: Adapted from Federal Highway Administration (*10*).

5. WHAT'S NEW IN THE HCM SIXTH EDITION

OVERVIEW

Research Basis for the HCM Sixth Edition

This section describes the new research incorporated into the HCM as part of the development of the Sixth Edition. Exhibit 1-2 lists the major research projects that contributed to this edition. The impacts of these and other projects on individual HCM chapters are described later in this section.

Reorganization from the HCM 2010

The Sixth Edition retains the HCM 2010's basic structure, with three printed volumes and one online-only volume. However, some noticeable changes have occurred as a result of the need to incorporate research on topics new to the HCM (e.g., travel time reliability, managed lanes) while keeping the size of the printed HCM similar to both the HCM2000 and the HCM 2010. The following are the most significant changes:

- Example problems have been moved from the Volume 2 and 3 chapters into the corresponding Volume 4 supplemental chapter.
- Two chapters related to travel time reliability (Chapter 11, Freeway Reliability Analysis, and Chapter 17, Urban Street Reliability and ATDM) have been added. Furthermore, the Volume 2 chapters on basic freeway segments and multilane highways have been combined into a single chapter. As a result, the chapter numbers for most Volume 2 and 3 chapters have been incremented by one relative to the HCM 2010.
- The Volume 2 and 3 chapters provide a more consistent set of sections. They generally contain an introduction and sections on concepts, motorized vehicle methodology, extensions to the methodology, modal methodologies (if applicable), and applications. Many Applications sections include a new Example Results subsection that illustrates the sensitivity of results to various methodological inputs and depicts typical ranges of results.
- Additional information on input data needs, data sources, default values, and interpretation of results has been added to Volume 2 and 3 chapters to assist practitioners in applying HCM methods, particularly when software is used.
- Material from the three emerging topics chapters on travel time reliability and managed lanes (36–38) that were adopted after the publication of the HCM 2010 has been incorporated into the applicable freeway and urban streets chapters; therefore, these chapters no longer exist.
- Volume 4 chapter numbers remain the same, except that Concepts: Supplemental is now Chapter 36; ATDM: Supplemental is now Chapter 37; and a new Chapter 35 has been added to supplement Chapter 24, Off-Street Pedestrian and Bicycle Facilities.

Exhibit 1-2
Major Research Projects Contributing to the HCM Sixth Edition

Project	Project Title	Project Objective(s)
NCFRP 41	Incorporating Truck Analysis into the *Highway Capacity Manual*	Develop improved capacity and LOS techniques for better evaluation of the effects of trucks on other modes of transportation and vice versa, for interrupted- and uninterrupted-flow facilities.
NCHRP 03-96	Analysis of Managed Lanes on Freeway Facilities	Develop methods for the performance assessment and capacity analysis of managed lanes on freeways.
NCHRP 03-107	Work Zone Capacity Methods for the *Highway Capacity Manual*	Develop improved material on the capacity of work zones on freeways, urban streets, and two-lane highways suitable for incorporation into the HCM.
NCHRP 03-100	Evaluating the Performance of Corridors with Roundabouts	Collect travel time field data for roundabouts in series and develop models for travel time prediction in an urban street context.
NCHRP 03-115	Production of a Major Update to the 2010 *Highway Capacity Manual*	Update the HCM 2010 to support the performance measure requirements of the Moving Ahead for Progress in the 21st Century Act, travel time reliability analysis, and ATDM strategy evaluation, while maintaining its support of the more traditional system planning, design, and operations activities.
NCHRP 07-22	Planning and Preliminary Engineering Applications Guide to the *Highway Capacity Manual*	Develop guidance, illustrated with case studies, on appropriate use of the HCM for a broad spectrum of planning and preliminary engineering applications, including scenario planning, coordinated use with other models, and use in evaluating oversaturated conditions in a planning context.
SHRP 2 L08	Incorporation of Travel Time Reliability into the *Highway Capacity Manual*	Determine how data and information on the impacts of differing causes of nonrecurrent congestion (incidents, weather, work zones, special events, etc.) in the context of freeway and urban street capacity can be incorporated into the performance measure estimation methods contained in the HCM.
Federal Highway Administration (FHWA-HOP-13-042)	Guide for Highway Capacity Analysis and Operations Analysis of Active Transportation and Demand Management Strategies	Develop HCM-related methodologies and measures of effectiveness for evaluating the impacts of ATDM strategies on highway and street system demand, capacity, and performance.
Federal Highway Administration (TOPR 34)	Accelerating Roundabout Implementation in the United States	Collect new roundabout field data, compare fit of new data to HCM 2010 model, and determine best course of action to improve fit.
Federal Highway Administration (Saxton Lab TOPR 2)	HCM Chapters; Guidance for Alternative Intersections; Interchanges	Collect field data and develop methodologies for HCM operational analysis for diverging diamond interchanges, restricted crossing U-turn intersections, median U-turn intersections, and displaced left-turn intersections.

A new *Planning and Preliminary Engineering Applications Guide to the HCM* (*9*) has been added to Volume 4. It provides guidance on effectively applying the HCM to a broad range of planning and preliminary engineering applications, on considering different project stages and scales, and on the role of the HCM in system performance monitoring. The guide includes a series of case study examples.

METHODOLOGICAL CHANGES BY SYSTEM ELEMENT

Freeway Facilities

The core methodology for estimating freeway performance measures for a single analysis period is contained in Chapter 10. The following changes and additions have been made to the methodology:

- The methodology has been revised to present individual steps more clearly and to distinguish steps performed by the user from those typically automated in software.
- A method has been added for evaluating freeway work zones.
- Material on evaluating managed lanes on freeway facilities, previously appearing in former Chapter 38, has been integrated into the chapter.
- New research has been incorporated on truck effects on freeway operations.
- A discussion has been added on estimating the effects of ATDM strategies on freeway operations on a single typical day (as opposed to a year-long analysis in a reliability context, which is covered in Chapter 11, Freeway Reliability Analysis).
- The guidance on freeway facility segmentation has been improved, and HCM segments and freeway analysis sections used in modern freeway data sources have been distinguished.

Chapter 25, Freeway Facilities: Supplemental, describes a new procedure for calibrating the methodology to existing conditions through the use of capacity and speed adjustment factors (CAFs and SAFs). It provides a new mixed-flow methodology for estimating truck performance on composite grades and a simplified planning method for freeway facilities. It also contains example problems illustrating the new Chapter 10 and 11 methodologies.

Freeway Reliability Analysis

Chapter 11 incorporates and updates the freeway travel time reliability material from former Chapters 36 and 37. It integrates the previous separate reliability and ATDM methods and provides a new process for calibrating the method to existing conditions. The description of the computational steps has been revised to present individual steps more clearly and to distinguish steps performed by the user from those typically automated in software, to be consistent with changes in Chapter 10.

The scenario generation process for freeway reliability analysis has been revised to reduce the number of scenarios needed for a reliability analysis and to improve the way in which weather and incident effects are accounted for in the scenarios. (The new scenario generation approach is discussed in detail in Chapter 25, Freeway Facilities: Supplemental.) Finally, a planning-level reliability methodology is presented.

Basic Freeway and Multilane Highway Segments

The chapters on basic freeway segments and multilane highways have been merged into a single Chapter 12, since the methods for these system elements are similar. The methodology has changed as follows:

- The speed–flow equation has been modified to provide one unified equation across all basic and multilane highway segments.
- New research has been incorporated on truck effects on freeway operations, which has resulted in revised truck passenger car equivalent tables and service volume tables.
- The method for evaluating basic managed lane segments has been integrated into the chapter.
- The method increases the emphasis on calibration through CAFs and SAFs.
- The driver population factor has been removed; the effects of nonfamiliar drivers on flow are handled instead through CAFs and SAFs.
- The density at capacity of multilane highway segments has been revised to a constant 45 passenger cars per mile per lane, consistent with basic freeway segments.
- The LOS E–F range for multilane highway segments has been revised to reflect the revised density at capacity.
- New speed–flow curves and capacities are provided for multilane highways for 65- and 70-mi/h free-flow speeds.

Chapter 26, Freeway and Highway Segments: Supplemental, provides a new method for measuring capacity in the field, a new method for evaluating truck performance on extended grades, and example problems related to the new methods.

Freeway Weaving Segments

Chapter 13 incorporates the methods for evaluating managed lane weaving segments, managed lane access segments, and cross-weave effects. The chapter increases the emphasis on calibration through the application of CAFs and SAFs. Chapter 27, Freeway Weaving: Supplemental, provides example problems that illustrate the new methods.

Freeway Merge and Diverge Segments

The method for evaluating managed lane merge and diverge segments has been integrated into Chapter 14. The chapter provides new formalized guidance for aggregating merge and diverge segment densities for segments with three or more lanes and increases the emphasis on calibration through the application of CAFs and SAFs. Similar to the other freeway chapters, discussion of managed lane merge and diverge segments has been added. Chapter 28, Freeway Merges and Diverges: Supplemental, provides example problems that illustrate the new methods.

Two-Lane Highways

No significant changes have been made to the Chapter 15 methodology, but additional guidance has been provided on applying the method and interpreting its results. In addition, some steps in the methodology that previously were always skipped (i.e., they were not needed in calculating LOS for a particular two-lane highway class) have been made optional, to clarify that they can be applied if the user is interested in determining the performance measure calculated in that methodological step.

Urban Street Facilities

The following changes have been made in Chapter 16:

- The service measure average travel speed of through vehicles as a percentage of base free-flow speed has been changed to the average travel speed of through vehicles. No change in LOS results is intended by this revision, but the new units and the use of rounded values will likely result in a few segments near a LOS threshold having a LOS one letter higher or lower.
- The threshold for LOS A has been changed from 85% of base free-flow speed to average through-vehicle travel speed values equivalent to 80% of the base free-flow speed.
- A procedure has been added for evaluating facilities that include segments experiencing sustained spillback.
- Pedestrian and bicycle LOS scores are now weighted by travel time instead of segment length.

Urban Street Reliability and ATDM

Chapter 17 is a new chapter in Volume 3. It incorporates content from Chapter 35 (Active Traffic Management) in the HCM 2010 and Chapters 36 (Travel Time Reliability) and Chapter 37 (Travel Time Reliability: Supplemental) that were adopted after the publication of the HCM 2010. New conceptual information about ATDM and techniques to evaluate ATDM strategies have been added to the prior content.

Urban Street Segments

The following changes have been made in Chapter 18:

- The service measure average travel speed of through vehicles as a percentage of base free-flow speed has been changed to the average travel speed of through vehicles. No change in LOS results is intended by this revision, but the new units and the use of rounded values will likely result in a few segments near a LOS threshold having a LOS one letter higher or lower.
- The threshold for LOS A has been changed from 85% of base free-flow speed to average through-vehicle travel speed values equivalent to 80% of the base free-flow speed.

- A procedure has been added for evaluating segments with midsegment lane blockage.
- The procedure for predicting segment queue spillback time has been revised to improve its accuracy.
- A new adjustment factor for parking activity has been added to the base free-flow speed calculation.
- The procedure can now evaluate segments that have roundabouts as boundary intersections.
- The procedure for computing volume balance for flows into and out of a segment was revised to ensure that right-turn-on-red vehicles are considered.
- Pedestrian and bicycle LOS scores are now based on a weighted link and intersection score. The weight for the link is link travel time and the weight for the intersection is delay at the intersection.
- The unsignalized conflicts factor term for the bicycle mode has been revised to consider 20 conflict points per mile as the base (no-effect) condition, rather than 0 conflict points per mile.
- The default bus acceleration rate was changed to 3.3 ft/s^2 from 4.0 ft/s^2.

Chapter 30, Urban Street Segments: Supplemental, provides a new procedure for estimating travel time on an urban street segment bounded by one or more roundabouts. In addition, the chapter's urban street segment planning application has added a f_{pa} term to calculate the progression adjustment factor. This factor was included in the HCM2000 but deleted for the HCM 2010. It has been brought back to minimize the differences in the predicted LOS when the HCM2000 method and the Sixth Edition's planning application are compared.

Signalized Intersections

The following changes have been made in Chapters 19 and 31:

- Delay for unsignalized movements is now considered in the calculation of approach delay and intersection delay. The analyst will have to provide these delays as input values.
- A combined saturation flow adjustment factor for heavy vehicles and grade is incorporated in the method. It replaces the previous individual factors for heavy vehicles and grade.
- New saturation flow adjustment factors are provided for work zone presence at the intersection, midsegment lane blockage, and a downstream segment with sustained spillback.
- A new planning application is provided, which simplifies the input data requirements and calculations.

STOP-Controlled Intersections

The application of the peak hour factor has been clarified in Chapter 20, Two-Way STOP-Controlled Intersections, and in Chapter 21, All-Way STOP-Controlled Intersections.

Roundabouts

The roundabout capacity models in Chapter 22 have been updated on the basis of new Federal Highway Administration (FHWA) research, a calibration procedure has been provided, and the application of the peak hour factor has been clarified.

Ramp Terminals and Alternative Intersections

Chapter 23 has been expanded to address a wider variety of distributed intersections—groups of two or more intersections that, by virtue of close spacing and displaced or distributed traffic movements, are operationally interdependent and are thus best analyzed as a single unit. Distributed intersections include interchange ramp terminals as well as a variety of alternative intersection and interchange forms where one or more traffic movements are rerouted to nearby secondary junctions. Interchange and intersection forms that are now addressed by the chapter's methodologies include diverging diamond interchanges, restricted crossing U-turn intersections, median U-turn intersections, and displaced left-turn intersections.

Local terminology for these alternative intersection types may be different—see Chapter 23 for details.

To accommodate the new material, the chapter has been reorganized into three parts:

A. Distributed Intersection Concepts,

B. Interchange Ramp Terminal Evaluation, and

C. Alternative Interchange Evaluation.

To allow different intersection forms to be compared on an equal basis, a new performance measure, experienced travel time, has been defined. It incorporates the sum of control delays experienced by a given movement through a distributed intersection plus any extra distance travel time experienced by rerouted movements. LOS in this chapter is now defined on the basis of experienced travel time.

Chapter 34, Interchange Ramp Terminals: Supplemental, provides new example problems demonstrating the application of the methodology.

Off-Street Pedestrian and Bicycle Facilities

No significant changes have been made in the Chapter 24 methodology, but additional guidance has been added on applying the method and interpreting its results. Some variable names and equations have been modified to improve their understandability without affecting the computational results.

6. COMPANION DOCUMENTS

Throughout its 60-year history, the HCM has been one of the fundamental reference works used by transportation engineers and planners. However, it is but one of a number of documents that play a role in the planning, design, and operation of transportation facilities and services. The HCM provides tools for evaluation of the performance of highway and street facilities in terms of operational and quality-of-service measures. This section describes companion documents to the HCM that cover important topics beyond the HCM's scope.

HIGHWAY SAFETY MANUAL

The *Highway Safety Manual* (HSM) (*11*) provides analytical tools and techniques for quantifying the safety effects of decisions related to planning, design, operations, and maintenance. The information in the HSM is provided to assist agencies as they integrate safety into their decision-making processes. It is a nationally used resource document intended to help transportation professionals conduct safety analyses in a technically sound and consistent manner, thereby improving decisions made on the basis of safety performance.

A POLICY ON GEOMETRIC DESIGN OF HIGHWAYS AND STREETS

The American Association of State Highway and Transportation Officials' *A Policy on Geometric Design of Highways and Streets* ("Green Book") (*12*) provides design guidelines for roadways ranging from local streets to freeways, in both urban and rural locations. The guidelines "are intended to provide operational efficiency, comfort, safety, and convenience for the motorist" and to emphasize the need to consider other modal users of roadway facilities.

MANUAL ON UNIFORM TRAFFIC CONTROL DEVICES

FHWA's *Manual on Uniform Traffic Control Devices* (MUTCD) (*13*) is the national standard for traffic control devices for any street, highway, or bicycle trail open to public travel. Of particular interest to HCM users are the sections of the MUTCD pertaining to warrants for all-way STOP control and traffic signal control, signing and markings to designate lanes at intersections, and associated considerations of adequate roadway capacity and less restrictive intersection treatments.

TRANSIT CAPACITY AND QUALITY OF SERVICE MANUAL

The TCQSM (*6*) is the transit counterpart to the HCM. The manual contains background, statistics, and graphics on the various types of public transportation, and it provides a framework for measuring transit availability, comfort, and convenience from the passenger point of view. The manual contains quantitative techniques for calculating the capacity of bus, rail, and ferry transit services and transit stops, stations, and terminals.

TRAFFIC ANALYSIS TOOLBOX

At the time of writing, FHWA had produced 14 volumes of the *Traffic Analysis Toolbox* (*14*), in addition to documents providing guidance on the selection and deployment of a range of traffic analysis tools, including the HCM. Four volumes of the *Toolbox* provide general guidance on the use of traffic analysis tools:

A useful reference on traffic operations modeling is FHWA's Traffic Analysis Toolbox.

- *Volume I: Traffic Analysis Tools Primer* (*15*) presents a high-level overview of the different types of traffic analysis tools and their role in transportation analyses.
- *Volume II: Decision Support Methodology for Selecting Traffic Analysis Tools* (*16*) identifies key criteria and circumstances to consider in selecting the most appropriate type of traffic analysis tool for the analysis at hand.
- *Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software* (*17*) provides a recommended process for using traffic microsimulation software in traffic analyses.
- *Volume VI: Definition, Interpretation, and Calculation of Traffic Analysis Tools Measures of Effectiveness* (*18*) provides information and guidance on which measures of effectiveness should be produced for a given application, how they should be interpreted, and how they are defined and calculated in traffic analysis tools.

The Traffic Analysis Toolbox *is available at http://ops.fhwa.dot.gov/trafficanalysistools/.*

Other volumes of the *Toolbox* deal with the use of alternative tools for specific application scenarios. They are referenced when appropriate in specific HCM chapters.

7. REFERENCES

Some of these references can be found in the Technical Reference Library in Volume 4.

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17. Dowling, R., A. Skabardonis, and V. Alexiadis. *Traffic Analysis Toolbox Volume III: Guidelines for Applying Traffic Microsimulation Modeling Software.* Report FHWA-HRT-04-040. Federal Highway Administration, Washington, D.C., June 2004.

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CHAPTER 2
APPLICATIONS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

OVERVIEW

Applications of the *Highway Capacity Manual* (HCM) range from the highly detailed to the highly generalized. The HCM can be applied to roadway system elements varying from individual points to an entire transportation system, to a number of travel modes that can be considered separately or in combination, and to several types of roadway and facility operating conditions. This chapter introduces the wide range of potential HCM applications. It also introduces the travel modes and roadway operating conditions to which the HCM can be applied.

HCM analysis levels.

The HCM can be applied at the *operational, design, preliminary engineering,* and *planning* analysis levels. The required input data typically remain the same at each analysis level, but the degree to which analysis inputs use default values instead of actual measured or forecast values differs. In addition, operational analyses and planning and preliminary engineering analyses frequently evaluate the level of service (LOS) that will result from a given set of inputs, whereas design analyses typically determine which facility characteristics will be needed to achieve a desired LOS.

Travel modes and roadway system elements addressed by the HCM.

The travel modes covered by the HCM include *motorized vehicles* [consisting of automobiles, light and heavy trucks, recreational vehicles (RVs), buses, and motorcycles], *pedestrians,* and *bicycles.* Some chapters also provide methods specific to *trucks* (e.g., single-unit trucks, tractor-trailers) and *public transit* vehicles operating on urban streets. The HCM's motorized vehicle methods assess the overall operation and quality of service of a traffic stream composed of a mix of vehicle types, while the truck and transit methods specifically address the operation (and, for transit, quality of service) of those modes.

From smallest to largest, roadway system elements include points, segments, facilities, corridors, areas, and systems.

All of these modes operate on a variety of roadway system elements, including *points* (e.g., intersections); *segments* (e.g., lengths of roadways between intersections); *facilities* (aggregations of points and segments); *corridors* (parallel freeway and arterial facilities); and, at the largest geographic scales, *areas* and *systems.*

HCM methodologies are provided both for *uninterrupted-flow* facilities, which have no fixed causes of delay or interruption external to the traffic stream, and for *interrupted-flow* facilities, on which traffic control devices such as traffic signals and STOP signs periodically interrupt the traffic stream. HCM analyses are applicable to *undersaturated* conditions (where demand is less than a roadway system element's capacity) and, in certain situations, to *oversaturated* conditions (where demand exceeds capacity).

Individual methodological chapters describe the extent to which the HCM can be used for oversaturated analyses. Chapter 6 describes alternative analysis tools that may be applied in situations in which the HCM cannot be used.

Finally, measures generated by HCM methodologies can be used for more than just stand-alone traffic analyses. This chapter describes potential applications of HCM methodologies to noise, air quality, economic, and multimodal planning analyses.

CHAPTER ORGANIZATION

Section 2 of this chapter describes the levels of analysis at which the HCM can be applied and introduces discussion of the analyst's need to balance the analysis objectives with the data requirements and computational complexity associated with different analysis levels and tools.

Section 3 defines the roadway system elements used by the HCM, introduces the service measures defining LOS for each system element, and provides guidance on applying HCM methods to a combined analysis of multiple facilities (e.g., corridors, areas, and systems).

Section 4 defines the travel modes for which the HCM provides analysis methods. Section 5 defines the types of operating conditions that can be observed on roadways. Section 6 discusses potential applications of HCM methods to support other kinds of analyses, such as air quality or noise analyses. Finally, Section 7 provides a list of references cited in this chapter.

RELATED HCM CONTENT

Other HCM content related to this chapter includes the following:

- Chapter 3, Modal Characteristics, which describes travel demand patterns associated with different modes, the types of transportation facilities used by these modes, and the interactions that occur between modes;
- Chapter 4, Traffic Operations and Capacity Concepts, which presents flow and capacity concepts by mode, along with operational performance measures that can be used to describe modal operations;
- Chapter 5, Quality and Level-of-Service Concepts, which presents measures that can be used to describe the service quality experienced by users of different modes;
- Chapter 6, HCM and Alternative Analysis Tools, which provides detailed guidance on matching potential analysis tools to analysis needs; and
- The *Planning and Preliminary Engineering Applications Guide to the HCM*, found in online Volume 4, which provides detailed guidance on applying HCM methods to the planning and preliminary engineering levels of analysis.

2. LEVELS OF ANALYSIS

OVERVIEW

Any given roadway operations analysis can be performed at different levels of detail, depending on the purpose of the analysis and the amount of information available. Typically, as an analysis becomes more detailed, its data requirements increase, the analysis area shrinks, the time requirements increase, and the degree of precision in the estimated performance improves (*1*).

The HCM defines three primary levels of analysis. From the most to the least detailed, these are as follows:

In order of most to least detailed, the three primary levels of analysis used in the HCM are operational, design, and planning and preliminary engineering.

- *Operational analysis* typically focuses on current or near-term conditions. It involves detailed inputs to HCM procedures, with no or minimal use of default values.
- *Design analysis* typically uses HCM procedures to identify the characteristics of a transportation facility that will allow it to operate at a desired LOS, with some use of default values.
- *Planning* and *preliminary engineering analyses* typically focus on initial problem identification, long-range analyses, and performance monitoring applications, where many facilities or alternatives must be evaluated quickly or when specific input values to procedures are not known. The extensive use of default values is required.

The typical usage of each of these analysis levels is described in the following subsections.

OPERATIONAL ANALYSIS

Operational analyses are applications of the HCM generally oriented toward current or near-term conditions. They aim at providing information for decisions on whether there is a need for improvements to an existing point, segment, or facility. Occasionally, an analysis is made to determine whether a more extensive planning study is needed. Sometimes the focus is on a network, or part of one, that is approaching oversaturation or an undesirable LOS: When, in the near term, is the facility likely to fail (or fail to meet a desired LOS threshold)? To answer this question, an estimate of the service flow rate allowable under a specified LOS is required.

The concept of LOS is described in Chapter 5, Quality and Level-of-Service Concepts.

HCM analyses also help practitioners make decisions about operating conditions. Typical alternatives often involve the analysis of appropriate lane configurations, alternative traffic control devices, signal timing and phasing, spacing and location of bus stops, frequency of bus service, and addition of a managed (e.g., high-occupancy vehicle) lane or a bicycle lane. The analysis produces operational measures for a comparison of the alternatives.

Because of the short-term focus of operational analyses, detailed inputs can be provided to the models. Many of the inputs may be based on field measurements of traffic, physical features, and control parameters. Generally, the use of default values at this level of analysis is inappropriate.

DESIGN ANALYSIS

Design analyses primarily apply the HCM to establish the detailed physical features that will allow a new or modified facility to operate at a desired LOS. Design projects are usually targeted for mid- to long-term implementation. Not all the physical features that a designer must determine are reflected in the HCM models. Typically, analysts using the HCM seek to determine such elements as the basic number of lanes required and the need for auxiliary or turning lanes. However, an analyst can also use the HCM to establish values for elements such as lane width, steepness of grade, length of added lanes, size of pedestrian queuing areas, widths of sidewalks and walkways, and presence of bus turnouts.

The data required for design analyses are fairly detailed and are based substantially on proposed design attributes. However, the intermediate- to long-term focus of the work will require use of some default values. This simplification is justified in part by the limits on the accuracy and precision of the traffic predictions with which the analyst is working.

PLANNING AND PRELIMINARY ENGINEERING ANALYSES

Planning analyses are applications of the HCM generally directed toward broad issues such as initial problem identification (e.g., screening a large number of locations for potential operations deficiencies), long-range analyses, and regional and statewide performance monitoring. An analyst often must estimate when the operation of the current and committed systems will fall below a desired LOS. Preliminary engineering analyses are often conducted to support planning decisions related to roadway design concept and scope and when alternatives analyses are performed. These studies can also assess proposed systemic policies, such as lane use control for heavy vehicles, systemwide freeway ramp metering and other intelligent transportation system applications, and the use of demand management techniques (e.g., congestion pricing) (2).

Planning and preliminary engineering analyses typically involve situations in which not all of the data needed for the analysis are available. Therefore, both types of analyses frequently rely on default values for many analysis inputs. Planning analyses may default nearly all inputs—for example, through the use of generalized service volume tables. Preliminary engineering analyses will typically fall between planning and design analyses in the use of default values.

Generalized service volume tables provide the maximum hourly or daily traffic volume that achieves a particular LOS, given a defined set of assumptions about a roadway's characteristics.

MATCHING THE ANALYSIS TOOL TO THE ANALYSIS LEVEL

Each methodological chapter in Volumes 2 and 3 has one core computational methodology. The degree to which defaulted or assumed values are used as inputs determines whether the HCM method is being applied at an operational, design, preliminary engineering, or planning level. However, the basic computational steps are the same regardless of the analysis level.

Some planning analyses (e.g., a long-range planning study where many input values, such as forecast volumes, are uncertain) may not require the level of precision provided by a core HCM methodology. Other kinds of planning analyses (e.g., sketch planning) may need to evaluate a large number of alternatives quickly. In either case, the analysis objective is to make a rough determination of whether a roadway facility will perform adequately rather than to estimate a particular performance characteristic, such as speed or delay, precisely. For these situations, the HCM and its companion *Planning and Preliminary Engineering Applications Guide to the HCM* (*1*) provide tools (e.g., service volume tables, quick estimation methods) that require less input data and fewer calculations, and they produce correspondingly less precise results.

Some operational analyses may require more detail (e.g., minute-by-minute roadway operations, evaluation of individual vehicle performance) than HCM methods are designed to produce. In other cases, a limitation of an HCM method may make its use inappropriate for a given analysis. In these situations, an analyst will need to apply an alternative analysis tool to complete the analysis.

Chapter 6, HCM and Alternative Analysis Tools, describes the range of HCM-based and alternative analysis tools available for analyzing roadway operations and quality of service and provides guidance on selecting an appropriate tool to meet a particular analysis need.

3. ROADWAY SYSTEM ELEMENTS

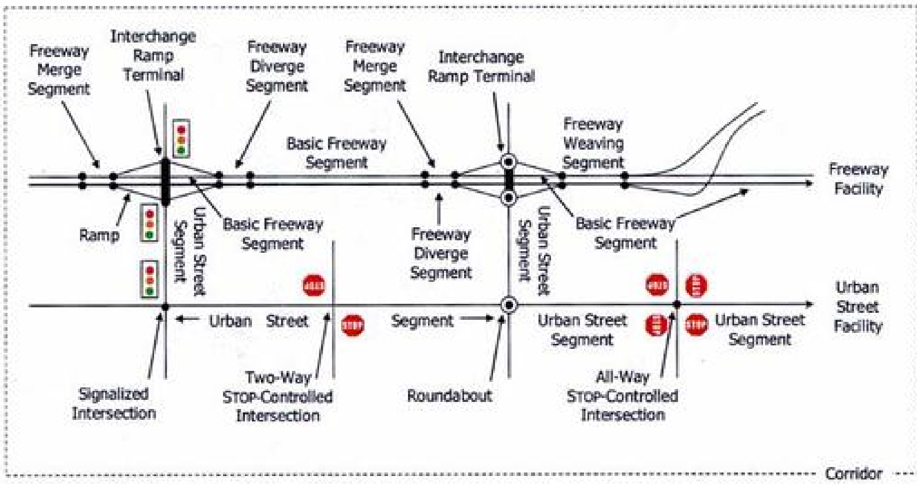
TYPES OF ROADWAY SYSTEM ELEMENTS

Of the six types of roadway system elements, the HCM focuses on points, segments, and facilities.

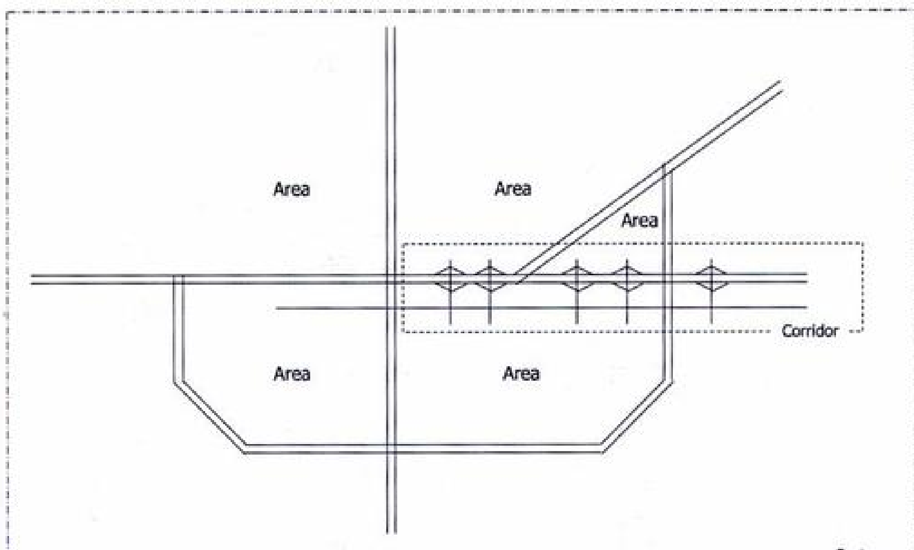
The HCM defines six main types of roadway system elements. From smallest to largest, the elements are points, segments, facilities, corridors, areas, and systems. The focus of the HCM is on the first three: points, segments, and facilities. Exhibit 2-1 illustrates the spatial relationships of these elements, and the following sections provide details about each system element type.

Exhibit 2-1
Illustrative Roadway System Elements

Note that a two-way STOP-controlled intersection does not normally divide the uncontrolled urban street into two segments.



(a) Points, Segments, Facilities, and Corridors



(b) Corridors, Areas, and Systems

Points

Points are places along a facility where (*a*) conflicting traffic streams cross, merge, or diverge; (*b*) a single traffic stream is regulated by a traffic control device; or (*c*) there is a significant change in the segment capacity (e.g., lane drop, lane addition, narrow bridge, significant upgrade, start or end of a ramp influence area).

Some points, such as interchange ramp terminals, may actually have a significant physical length associated with them, as suggested by Exhibit 2-1(a). For urban street facility analysis, points are treated as having zero length—all of the delay occurs at the point. For freeway facility analysis, points are used to define the endpoints of segments, but they have no associated performance measures or capacity, since these items are calculated at the segment level.

Freeway points are used only to define the endpoints of segments—performance measures and capacity are not defined for them.

Urban street points have a physical length but are treated as having zero length for facility analysis purposes.

Segments

A segment is the length of roadway between two points. Traffic volumes and physical characteristics generally remain the same over the length of a segment, although small variations may occur (e.g., changes in traffic volumes on a segment resulting from a low-volume driveway). Segments may or may not be directional. The HCM defines basic freeway and multilane highway segments, freeway weaving segments, freeway merge and diverge segments, two-lane highway segments, and urban street segments.

Facilities

Facilities are lengths of roadways, bicycle paths, and pedestrian walkways composed of a connected series of points and segments. Facilities may or may not be directional and are defined by two endpoints. The HCM defines freeway facilities, two-lane highway facilities, urban street facilities, and pedestrian and bicycle facilities.

The types of facilities addressed by the HCM are described in Chapter 3, Modal Characteristics.

Corridors

Corridors are generally a set of parallel transportation facilities designed to move people between two locations. For example, a corridor may consist of a freeway facility and one or more parallel urban street facilities. There may also be rail or bus transit service on the freeway, the urban streets, or both, and transit service could be provided within a separate, parallel right-of-way. Pedestrian or bicycle facilities may also be present within the corridor as designated portions of roadways and as exclusive, parallel facilities.

Areas

Areas consist of an interconnected set of transportation facilities serving movements within a specified geographic space as well as movements to and from adjoining areas. The primary factor distinguishing areas from corridors is that the facilities within an area need not be parallel to each other. Area boundaries can be set by significant transportation facilities, political boundaries, or topographic features such as ridgelines or major bodies of water.

Systems

Systems are composed of all the transportation facilities and modes within a particular region. A large metropolitan area typically has multiple corridors passing through it, which divide the system into a number of smaller areas. Each area contains a number of facilities, which, in turn, are composed of a series of points and segments. Systems can also be divided into modal subsystems (e.g., the roadway subsystem, the transit subsystem) and into subsystems composed of specific roadway elements (e.g., the freeway subsystem, the urban street subsystem).

ANALYSIS OF INDIVIDUAL SYSTEM ELEMENTS

Chapter 5, Quality and Level-of-Service Concepts, describes each system element's service measure(s).

The HCM provides tools to help analysts estimate performance measures for individual elements of a multimodal transportation system, as well as guidance on combining those elements to evaluate larger portions of the system. Exhibit 2-2 tabulates the various system elements for which the HCM provides analysis methodologies in Volumes 2 and 3, the service measure(s) used to determine LOS for each mode operating on each system element, and the HCM performance measure that can be used to aggregate results to a system level. Some combinations of system elements and travel modes unite several performance measures into a single traveler perception model that is used to generate a LOS score; the components of each model are listed in Exhibit 2-3.

Exhibit 2-2
HCM Service Measures by System Element and Mode

System Element	HCM Chapter	Service Measure(s) by Mode: Automobile	Pedestrian	Bicycle	Transit	Systems Analysis Measure
Freeway facility	10	Density	--	--	--	Speed
Basic freeway segment	12	Density	--	--	--	Speed
Multilane highway	12	Density	--	LOS score[a]	--	Speed
Freeway weaving segment	13	Density	--	--	--	Speed
Freeway merge and diverge segments	14	Density	--	--	--	Speed
Two-lane highway	15	Percent time-spent-following, speed	--	LOS score[a]	--	Speed
Urban street facility	16	Speed	LOS score[a]	LOS score[a]	LOS score[a]	Speed
Urban street segment	18	Speed	LOS score[a]	LOS score[a]	LOS score[a]	Speed
Signalized intersection	19	Delay	LOS score[a]	LOS score[a]	--	Delay
Two-way stop	20	Delay	Delay	--	--	Delay
All-way stop	21	Delay	--	--	--	Delay
Roundabout	22	Delay	--	--	--	Delay
Ramp terminal, alternative intersection	23	Experienced travel time	--	--	--	Travel time
Off-street pedestrian–bicycle facility	24	--	Space, events[b]	LOS score[a]	--	Speed

Notes: [a] See Exhibit 2-3 for the LOS score components.
[b] Events are situations where pedestrians meet bicyclists.

ASSESSMENT OF MULTIPLE FACILITIES

The analysis of a transportation system starts with estimates of delay at the point and segment levels. Point delays arise from the effects of traffic control devices such as traffic signals and STOP signs. Segment delays combine the point delay incurred at the end of the segment with other delays incurred within the segment. Examples of the latter include delays caused by midblock turning activity into driveways, parking activity, and midblock pedestrian crossings. The HCM estimates segment speed instead of segment delay; however, segment speed can be converted into segment delay by using Equation 2-1.

Exhibit 2-3
Components of Traveler-Perception Models Used in the HCM

System Element	HCM Chapter	Mode	Model Components
Multilane and two-lane highways	12, 15	Bicycle	Pavement quality, perceived separation from motor vehicles, motor vehicle volume and speed
Urban street facility	16	Automobile	Weighted average of segment automobile LOS scores
		Pedestrian	Urban street segment and signalized intersection pedestrian LOS scores, midblock crossing difficulty
		Bicycle	Urban street segment and signalized intersection bicycle LOS scores, driveway conflicts
		Transit	Weighted average of segment transit LOS scores
Urban street segment	18	Automobile	Stops per mile, left-turn lane presence
		Pedestrian	Pedestrian density, sidewalk width, perceived separation from motor vehicles, motor vehicle volume and speed
		Bicycle	Perceived separation from motor vehicles, pavement quality, motor vehicle volume and speed
		Transit	Service frequency, perceived speed, pedestrian LOS
Signalized intersection	19	Pedestrian	Street crossing delay, pedestrian exposure to turning vehicle conflicts, crossing distance
		Bicycle	Perceived separation from motor vehicles, crossing distance
Off-street pedestrian–bicycle facility	24	Bicycle	Average meetings/minute, active passings/minute, path width, centerline presence, delayed passings

The automobile traveler perception model for urban street segments and facilities is not used to determine LOS, but it is included to facilitate multimodal analyses.

$$D_i = AVO_i \times d_i \left(\frac{L_i}{S_i} - \frac{L_i}{S_{0i}}\right)$$

Equation 2-1

where

D_i = person-hours of delay on segment i,

AVO_i = average vehicle occupancy on segment i (passengers/vehicle),

d_i = vehicle demand on segment i (vehicles),

L_i = length of segment i (mi),

S_i = average vehicle speed on segment i (mi/h), and

S_{0i} = free-flow speed of segment i (mi/h).

Segment delays are added together to obtain facility estimates, and the sum of the facility estimates yields subsystem estimates. Mean delays for each subsystem are then computed by dividing the total person-hours of delay by the total number of trips on the subsystem. Subsystem estimates of delay can be combined into total system estimates, but typically the results for each subsystem are reported separately.

Typically, only the segments that constitute the collector and arterial system are used to estimate system delay.

SYSTEM PERFORMANCE MEASUREMENT

System performance must be measured in more than one dimension. When a single intersection is analyzed, computation of only the peak-period delay may suffice; however, when a system is analyzed, the geographic extent, the duration of delay, and any shifts in demand among facilities and modes must also be considered (3).

An increase in congestion on one system element may result in a shift of demand to other system elements. Therefore, estimating system delay is an iterative process. HCM techniques can be used to estimate the delay resulting from a given demand, but not the demand resulting from a given delay.

System performance can be measured in the following six dimensions:

Dimensions of system performance.

- *Quantity of service*—the number of person miles and person-hours provided by the system,
- *Intensity of congestion*—the amount of congestion experienced by users of the system,

- *Duration of congestion*—the number of hours that congestion persists,
- *Extent of congestion*—the physical length of the congested system,
- *Variability*—the day-to-day variation in congestion, and
- *Accessibility*—the percentage of the populace able to complete a selected trip within a specified time.

Quantity of Service

Quantity of service measures the utilization of the transportation system in terms of the number of people using the system, the distance they travel (person miles of travel, PMT), and the time they require to travel (person-hours of travel, PHT). Dividing the PMT by the PHT gives the mean trip speed for the system.

Intensity of Congestion

The intensity of congestion can be measured by using total person-hours of delay and mean trip speed. Other metrics, such as mean delay per person trip, can also be used. In planning and preliminary engineering applications, intensity of congestion is sometimes measured in terms of the volume-to-capacity ratio or the demand-to-capacity ratio.

Duration of Congestion

A segment is congested if the demand exceeds the segment's discharge capacity.

The duration of congestion is measured in terms of the maximum amount of time that congestion occurs anywhere in the system. A segment is congested if the demand exceeds the segment's discharge capacity. Transit subsystem congestion can occur either when the passenger demand exceeds the capacity of the transit vehicles or when the need to move transit vehicles exceeds the vehicular capacity of the transit facility.

Extent of Congestion

The extent of congestion may be expressed in terms of the directional miles of facilities congested or—more meaningfully for the public—in terms of the maximum percentage of system miles congested at any one time.

Variability

Variability of congestion is expressed by measures of travel time reliability, including measures of travel time variability and measures of a given trip's success or failure in meeting a target travel time. Section 2 of Chapter 4, Traffic Operations and Capacity Concepts, discusses travel time reliability in detail.

Accessibility

Accessibility examines the effectiveness of the system from a perspective other than intensity. Accessibility can be expressed in terms of the percentage of trips (or persons) able to accomplish a certain goal—such as going from home to work—within a targeted travel time. Accessibility can also be defined in terms of a traveler's ability to get to and use a particular modal subsystem, such as transit. This definition is closer to the Americans with Disabilities Act's use of the term.

4. TRAVEL MODES

This section introduces the four major travel modes addressed by the HCM: automobile, pedestrian, bicycle, and transit. Chapter 3, Modal Characteristics, provides details about each mode that are important for HCM analyses.

MOTORIZED VEHICLE MODE

The motorized vehicle mode includes all motor vehicle traffic using a roadway. Thus, automobiles, trucks, RVs, motorcycles, and public transit buses are all considered members of the motorized vehicle mode for HCM analysis purposes. Because different motor vehicle types have different operating characteristics (to be discussed further in Chapter 3), the HCM uses the passenger car as a common basis of comparison. For example, trucks take up more roadway space than passenger cars and accelerate more slowly, particularly on upgrades. Therefore, in some cases, the HCM converts trucks into passenger car equivalents (e.g., an average truck uses the same roadway space as two passenger cars on a freeway with a level grade); in other cases, parameters used by HCM methods are adjusted to reflect the specific mix of vehicles in the traffic stream.

The HCM's motorized vehicle mode methods assess the operations and quality of service of a traffic stream consisting of a mix of vehicle types.

Some HCM chapters also provide information specific to trucks and public transit, which are treated as separate modes in those cases.

The HCM's LOS thresholds for the motorized vehicle mode are based on the perspective of automobile drivers. Therefore, automobile LOS measures may not reflect the perspective of drivers of other types of motorized vehicles, especially trucks. The HCM defines a separate *transit mode* to present LOS measures for public transit passengers.

LOS measures for the motorized vehicle mode represent the perspective of automobile drivers. Separate LOS measures for the transit mode are used to represent the perspective of transit passengers.

Analytical methods and performance measures that specifically describe truck operations and quality of service are a growing area of research and transportation agency interest. This edition of the HCM occasionally uses a separate *truck mode* to present truck-specific information; however, in most cases, trucks are analyzed as part of the motorized vehicle mode.

PEDESTRIAN MODE

The pedestrian mode consists of travelers along a roadway or pedestrian facility making a journey (or at least part of their journey) on foot. Pedestrians walk at different speeds, depending on their age, their ability, and environmental characteristics (e.g., grades and climate); HCM procedures generally account for this variability. Sidewalks and pathways may be used by more than just foot-based traffic—for example, inline skaters and persons in wheelchairs—but the HCM's LOS thresholds reflect the perspective of persons making a walking journey.

BICYCLE MODE

The bicycle mode consists of travelers on a roadway or pathway who are using a nonmotorized bicycle for their trip; bicycle LOS thresholds reflect their perspective. Mopeds and motorized scooters are not considered bicycles for HCM analysis purposes.

The companion TCQSM provides capacity and speed estimation procedures for transit vehicles and additional LOS measures for transit passengers.

TRANSIT MODE

Urban roadways are often shared with public transit buses and, occasionally, with rail transit vehicles such as streetcars and light rail vehicles. The HCM's urban street facility and segment chapters (Chapters 16 and 18) provide methods for assessing the quality of service of transit service from the passenger point of view. The companion *Transit Capacity and Quality of Service Manual* (TCQSM) (4) provides methods for assessing the capacity, speed, and quality of service of a variety of transit modes in both on- and off-street settings.

5. OPERATING CONDITIONS

The HCM provides methods for analyzing traffic flow under a variety of conditions. These conditions are introduced and defined in this section, since they are used repeatedly throughout the HCM. They are described more fully in Chapter 4, Traffic Operations and Capacity Concepts.

UNINTERRUPTED FLOW

Uninterrupted-flow facilities have no fixed causes of delay or interruption external to the traffic stream. Volume 2 of the HCM provides analysis methodologies for uninterrupted-flow facilities.

Uninterrupted-flow facilities have no fixed causes of delay or interruption external to the traffic stream.

Freeways and their components operate under the purest form of uninterrupted flow. There are no fixed interruptions to traffic flow, and access is controlled and limited to ramp locations. Multilane highways and two-lane highways can also operate under uninterrupted flow in long segments between points of fixed interruption. On multilane and two-lane highways, points of fixed interruption (e.g., traffic signals) as well as uninterrupted-flow segments must often be examined.

The traffic stream on uninterrupted-flow facilities is the result of individual vehicles interacting with each other and the facility's geometric characteristics. The pattern of flow is generally controlled only by the characteristics of the land uses that generate traffic using the facility, although freeway management and operations strategies—such as ramp metering, freeway auxiliary lanes, truck lane restrictions, variable speed limits, and incident detection and clearance—can influence traffic flow. Operations can also be affected by environmental conditions, such as weather or lighting; by pavement conditions; by work zones; and by the occurrence of traffic incidents (*5, 6*).

Uninterrupted flow describes the type of facility, not the quality of the traffic flow at any given time. The terms *oversaturated* and *undersaturated flow,* described below, reflect the quality of traffic flow. An oversaturated freeway is still an uninterrupted-flow facility because the causes of congestion are internal.

INTERRUPTED FLOW

Interrupted-flow facilities have fixed causes of periodic delay or interruption to the traffic stream, such as traffic signals, roundabouts, and STOP signs. Urban streets are the most common form of this kind of facility. Exclusive pedestrian and bicycle facilities are also treated as interrupted flow, since they may occasionally intersect other streets at locations where pedestrians and bicyclists do not automatically receive the right-of-way. Volume 3 of the HCM provides analysis methodologies for interrupted-flow facilities.

Interrupted-flow facilities have fixed causes of periodic delay or interruption to the traffic stream, such as traffic signals, roundabouts, and STOP signs.

The traffic flow patterns on an interrupted-flow facility are the result not only of vehicle interactions and the facility's geometric characteristics but also of the traffic control used at intersections and the frequency of access points to the facility. Traffic signals, for example, allow designated movements to occur only during certain portions of the signal cycle (and, therefore, only during certain portions of an hour). This control creates two significant outcomes. First, time becomes a factor affecting flow and capacity because the facility is not available for continuous use. Second, the traffic flow pattern is dictated by the type of control used. For instance, traffic signals create platoons of vehicles that travel along the facility as a group, with significant gaps between one platoon and the next. In contrast, all-way STOP-controlled intersections and roundabouts discharge vehicles more randomly, creating small (but not necessarily usable) gaps in traffic at downstream locations (*5, 7*).

UNDERSATURATED FLOW

Traffic flow during an analysis period (e.g., 15 min) is specified as *undersaturated* when the following conditions are satisfied: (*a*) the arrival flow rate is lower than the capacity of a point or segment, (*b*) no residual queue remains from a prior breakdown of the facility, and (*c*) traffic flow is unaffected by downstream conditions.

Free-flow speed is the average speed of traffic on a segment as volume and density approach zero.

Uninterrupted-flow facilities operating in a state of undersaturated flow will typically have travel speeds within 10% to 20% of the facility's free-flow speed, even at high flow rates, under base conditions (e.g., level grades, standard lane widths, good weather, no incidents). Furthermore, no queues would be expected to develop on the facility.

On interrupted-flow facilities, queues form as a natural consequence of the interruptions to traffic flow created by traffic signals and STOP and YIELD signs. Therefore, travel speeds are typically 30% to 65% below the facility's free-flow speed in undersaturated conditions. Individual cycle failures—where a vehicle has to wait through more than one green phase to be served—may occur at traffic signals under moderate- to high-volume conditions as a result of natural variations in the cycle-to-cycle arrival and service rate. Similarly, STOP- and YIELD-controlled approaches may experience short periods of significant queue buildup. However, as long as all of the demand on an intersection approach is served within a 15-min analysis period, including any residual demand from the prior period, the approach is considered to be undersaturated.

OVERSATURATED FLOW

Traffic flow during an analysis period is characterized as *oversaturated* when any of the following conditions is satisfied: (*a*) the arrival flow rate exceeds the capacity of a point or segment, (*b*) a queue created from a prior breakdown of a facility has not yet dissipated, or (*c*) traffic flow is affected by downstream conditions.

On uninterrupted-flow facilities, oversaturated conditions result from a bottleneck on the facility. During periods of oversaturation, queues form and extend backward from the bottleneck point. Traffic speeds and flows drop significantly as a result of turbulence, and they can vary considerably, depending on the severity of the bottleneck. Freeway queues differ from queues at undersaturated signalized intersections in that they are not static or "standing." On freeways, vehicles move slowly through a queue, with periods of stopping and movement. Even after the demand at the back of the queue drops, some time is required for the queue to dissipate because vehicles discharge from the queue at a slower rate than they do under free-flow conditions. Oversaturated conditions persist within the queue until the queue dissipates completely after a period of time during which demand flows are less than the capacity of the bottleneck.

On interrupted-flow facilities, oversaturated conditions generate a queue that grows backward from the intersection at a rate faster than can be processed by the intersection over the analysis period. Oversaturated conditions persist after demand drops below capacity until the residual queue (i.e., the queue over and above what would be created by the intersection's traffic control) has dissipated. A queue generated by an oversaturated unsignalized intersection dissipates more gradually than is typically possible at a signalized intersection.

If an intersection approach or ramp meter cannot accommodate all of its demand, queues may back into upstream intersections and adversely affect their performance. Similarly, if an interchange ramp terminal cannot accommodate all of its demand, queues may back onto the freeway and adversely affect the freeway's performance.

QUEUE DISCHARGE FLOW

A third type of flow, queue discharge flow, is particularly relevant for uninterrupted-flow facilities. Queue discharge flow represents traffic flow that has just passed through a bottleneck and, in the absence of another bottleneck downstream, is accelerating back to the facility's free-flow speed. Queue discharge flow is characterized by relatively stable flow as long as the effects of another bottleneck downstream are not present.

On freeways, this flow type is typically characterized by speeds ranging from 35 mi/h up to the free-flow speed of the freeway segment. Lower speeds are typically observed just downstream of the bottleneck. Depending on horizontal and vertical alignments, queue discharge flow usually accelerates back to the facility's free-flow speed within 0.5 to 1 mi downstream of the bottleneck. The queue discharge flow rate from the bottleneck is lower than the maximum flows observed before breakdown; this effect is discussed further in Section 2 of Chapter 10, Freeway Facilities Core Methodology.

6. HCM ANALYSIS AS PART OF A BROADER PROCESS

Since its first edition in 1950, the HCM has provided transportation analysts with tools for estimating traffic operational measures such as speed, density, and delay. It also has provided insights and specific tools for estimating the effects of traffic, roadway, and other conditions on the capacity of facilities. Over time, calculated values from the HCM have increasingly been used in other transportation work. The use of estimated or calculated values from HCM work as the foundation for estimating user costs and benefits in terms of economic value and environmental changes (especially air and noise) is particularly pronounced in transportation priority programs and in the justification of projects. This section provides examples of how HCM outputs can be used as inputs to other types of analyses.

NOISE ANALYSIS

At the time this chapter was written, federal regulations specifying noise abatement criteria stated that "in predicting noise levels and assessing noise impacts, traffic characteristics which will yield the worst hourly traffic noise impact on a regular basis for the design year shall be used" [23 CFR 772.17(b)]. The "worst hour" is usually taken to mean the loudest hour, which does not necessarily coincide with the busiest hour, since vehicular noise levels are directly related to speed. Traffic conditions in which large trucks are at their daily peak and in which LOS E conditions exist typically represent the loudest hour (*8*).

AIR QUALITY ANALYSIS

The 1990 Clean Air Act Amendments required state and local agencies to develop accurate emission inventories as an integral part of their air quality management and transportation planning responsibilities. Vehicular emissions are a significant contributor to poor air quality; therefore, the U.S. Environmental Protection Agency (EPA) has developed analysis procedures and tools for estimating emissions from mobile sources such as motorized vehicles. One input into the emissions model is average vehicle speed, which can be entered at the link (i.e., length between successive ramps) level, if desired. EPA's model is sensitive to average vehicle speed (i.e., a 20% change in average vehicle speed resulted in a greater than 20% change in the emissions estimate), which implies that accurate speed inputs are a requirement for accurate emissions estimates. The HCM is a tool recommended by EPA for generating speed estimates on freeways and arterials and collectors (*9–11*).

ECONOMIC ANALYSIS

The economic analysis of transportation improvements also depends to a large extent on information generated from the HCM. Road user benefits are directly related to reductions in travel time and delay, while costs are determined from construction of roadway improvements (e.g., addition of lanes, installation of traffic signals) and increases in travel time and delay. The following excerpt from the American Association of State Highway and Transportation Officials Green Book (*12*, p. 3-2) indicates the degree to which such analyses depend on the HCM:

> The [HCM] provides many tools and procedures to assist in the calculation of segment speeds. These procedures permit detailed consideration of segment features, including the effects of road geometry and weaving on the capacity and speed of a highway segment. Speed can be calculated for local streets and roads, highways and freeways using the [HCM]. The most accurate rendering of the effects of additional lanes on speed, therefore, is through the use of the [HCM] calculation procedures.

MULTIMODAL PLANNING ANALYSIS

An increasing number of jurisdictions are taking an integrated approach to multimodal transportation planning. That is, rather than developing plans for the automobile, transit, and pedestrian and bicycle modes in isolation, these jurisdictions evaluate trade-offs among the modes as part of their transportation planning and decision making. The HCM 2010 is designed to support those efforts. For example, Chapter 16, Urban Street Facilities, presents an integrated, multimodal set of LOS measures for urban streets. The other interrupted-flow chapters in Volume 3 also integrate pedestrian and bicycle measures, to the extent that research is available to support those measures.

SYSTEM PERFORMANCE MEASUREMENT

State and federal governments use HCM procedures in reporting transportation system performance. For example, the Federal Highway Administration's Highway Performance Monitoring System uses HCM procedures to estimate the capacity of highway sections and to determine volume-to-service flow ratios (*13*). In addition, the federal surface transportation funding act, the Moving Ahead for Progress in the 21st Century Act, established performance-based procedures for planning and project programming (*14*), and performance measures that the HCM can estimate are anticipated to play a role in these performance monitoring activities. Florida uses HCM procedures to estimate speeds on the state highway system as part of its mobility performance measures reporting.

SUMMARY

In summary, almost all economic analyses and all air and noise environmental analyses rely directly on one or more measures estimated or produced with HCM calculations. Exhibit 2-4 lists the motorized vehicle–based performance measures from this manual that are applicable to environmental or economic analyses.

Exhibit 2-4
HCM Motorized Vehicle Performance Measures for Environmental and Economic Analyses

Chapter	Motorized Vehicle Performance Measure	Analysis Types Appropriate for Use: Air	Noise	Economic
10. Freeway Facilities Core Methodology	Density[a]			
	Vehicle hours of delay			√
	Speed	√	√	√
	Travel time			√
12. Basic Freeway and Multilane Highway Segments	Density[a]			
	Speed	√	√	√
	v/c ratio	√		√
13. Freeway Weaving Segments	Density[a]			
	Weaving speed	√	√	√
	Nonweaving speed	√	√	√
14. Freeway Merge and Diverge Segments	Density[a]			
	Speed	√	√	√
15. Two-Lane Highways	Percent time-spent-following[a]			
	Speed[a]	√	√	√
16. Urban Street Facilities 18. Urban Street Segments	Speed[a]			
	Stop rate	√	√	√
	Running time	√		√
	Intersection control delay	√		√
19. Signalized Intersections 20. TWSC Intersections 21. AWSC Intersections 22. Roundabouts	Control delay[a]	√		√
	v/c ratio	√		√
23. Ramp Terminals and Alternative Intersections	Extra distance travel time[a]	√		√
	v/c ratio	√		√

Notes: [a] Chapter service measure.
TWSC = two-way STOP-controlled, AWSC = all-way STOP-controlled, *v/c* = volume to capacity.

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CHAPTER 3
MODAL CHARACTERISTICS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

OVERVIEW

Roadways serve users of many different modes: motorists, truck operators, pedestrians, bicyclists, and transit passengers. The roadway right-of-way is allocated among the modes through the provision of facilities that ideally serve each mode's needs. However, in many urban situations, the right-of-way is constrained by adjacent land development, which causes transportation engineers and planners to consider trade-offs in allocation of the right-of-way. Interactions among the modes that result from different right-of-way allocations are important to consider in analyzing a roadway, and the *Highway Capacity Manual* (HCM) provides tools for assessing these interactions. Local policies and design standards relating to roadway functional classifications are other sources of guidance on the allocation of right-of-way; safety and operational concerns should also be addressed.

CHAPTER ORGANIZATION

Chapter 3 introduces some basic characteristics of the travel modes addressed by the HCM. The following characteristics are considered in this chapter for each mode:

- Factors that contribute to a traveler's experience during a trip,
- Observed seasonal and daily variations in travel demand,
- Types of transportation facilities used by a given mode, and
- The interactions that occur between modes.

Chapters 4 and 5 continue the discussion of multimodal performance. Chapter 4 discusses traffic operations and capacity concepts and provides operational performance measures for each mode. Chapter 5 discusses quality and level-of-service (LOS) concepts and introduces the service measures for each mode that the HCM uses to assess transportation facilities from a traveler point of view.

2. MOTORIZED VEHICLE MODE

OVERVIEW

The HCM uses the term "automobile" for two-axle, four-wheel vehicles generally. It uses the term "passenger car" for a specific type of light vehicle (Federal Highway Administration Vehicle Class 2).

For the purpose of evaluating roadway operations, HCM methods consider all motorized vehicles—passenger cars, trucks, vans, buses, motorcycles, recreational vehicles, and so on—to be part of the overall traffic stream, but they take the unique characteristics of each vehicle type into account in the evaluation. In most cases in a U.S. context, the majority of the traffic stream consists of automobiles (i.e., two-axle, four-wheel vehicles); therefore, HCM methods convert trucks, buses, and other heavy vehicles into passenger car equivalents when the operation of traffic streams on roadways is analyzed.

In contrast, in evaluating roadway quality of service, the HCM's motorized vehicle methods primarily reflect the perspective of automobile drivers and not necessarily the perspectives of other motorized vehicle users. In some cases, the perspectives of the passengers or cargo within a vehicle may be of greatest interest. In such cases, the HCM defines additional modes—specifically, transit and truck—to address these perspectives. As discussed in Chapter 5, Quality and Level-of-Service Concepts, quality of service for the transit mode reflects the perspective of passengers using transit vehicles. The HCM does not yet define LOS for freight movement by truck, but some initial research has been conducted in this area (e.g., *1*).

VEHICLE AND HUMAN FACTORS

Three major elements affect driving: the vehicle, the roadway environment, and the driver. This section identifies motor vehicle and driver characteristics and how they are affected by the roadway's environment and physical properties.

General Vehicle Characteristics

This section provides a summary of the operating characteristics of motor vehicles that should be considered when a facility is analyzed. The major considerations are vehicle types and dimensions, turning radii and off-tracking, resistance to motion, power requirements, acceleration performance, and deceleration performance.

Motorized vehicles include passenger cars, trucks, vans, buses, recreational vehicles, and motorcycles. All of these vehicles have unique weight, length, size, and operational characteristics. In particular, *heavy vehicles*—vehicles with more than four tires touching the ground—accelerate and decelerate more slowly than passenger cars and can have difficulty in maintaining speed on upgrades. Heavy vehicles are larger than passenger cars, so they occupy more roadway space and create larger time headways between vehicles.

Use of passenger car equivalents to account for heavy vehicle presence in the traffic stream.

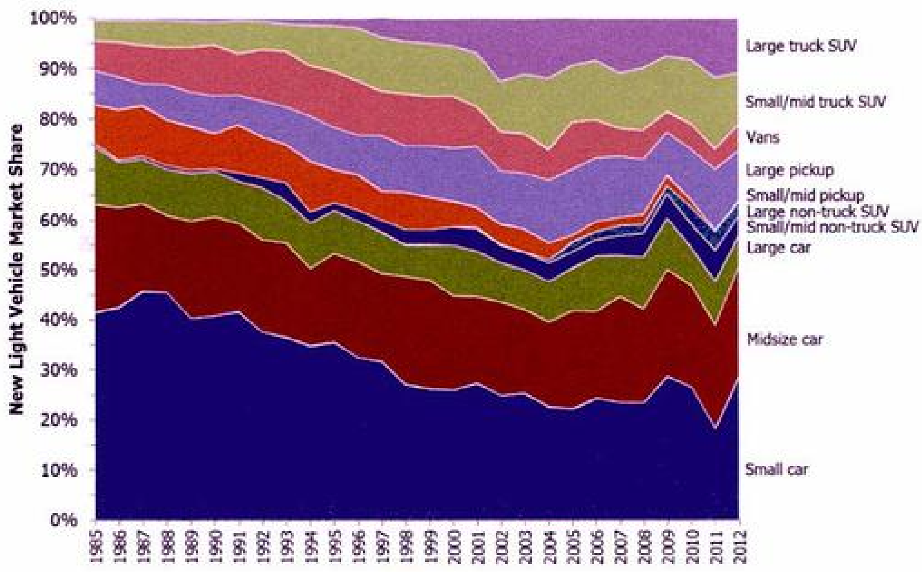
The HCM uses the concept of *passenger car equivalents* to convert the roadway space and time used by a given type of heavy vehicle into the equivalent number of passenger cars that could have used it, given identical roadway, traffic, and control conditions. This approach provides a common basis for evaluating roadway operations. Although the HCM expresses capacity in terms of the number of *passenger cars per hour* that can be served by a roadway system element, the number of *vehicles per hour* that can be served will be less than the number of passenger cars that can be served and will decrease as the percentage of heavy vehicles in the traffic stream increases.

Light Vehicle Characteristics

The composition of the light vehicle fleet in the United States has varied over time, with corresponding changes in typical vehicle dimensions and weights. As shown in Exhibit 3-1, passenger cars' share of new light-duty vehicle sales decreased from 75% in model year 1985 to a low of 48% in model year 2004 and subsequently increased to 57% by model year 2012 (*2*). These trends have been influenced by a number of factors, including fuel prices, increased popularity of other light vehicle classes (e.g., sport-utility vehicles), economic conditions, and short-term supply constraints (*3*).

Over the same time period, average passenger car acceleration rates have steadily improved. They increased from an average of 6.6 ft/s² when accelerating from 0 to 60 mi/h for model year 1985 cars to 8.5 ft/s² in 2000 and 9.4 ft/s² in 2013 (*3*). Maximum passenger car deceleration rates range between 10 and 25 ft/s², depending on road surface and tire conditions, with deceleration rates of 10 ft/s² or less considered reasonably comfortable for passenger car occupants (*4*). These rates are considered in designing traffic signal timing, computing fuel economy and travel time, and estimating how normal traffic flow resumes after a breakdown.

Exhibit 3-1
U.S. Light Vehicle Sales Trends, 1985–2012



Source: Davis et al. (*2*).
Note: SUV = sport-utility vehicle.

Heavy Vehicle Characteristics

Section 3 describes the characteristics of different types of trucks. Section 6 describes the characteristics of transit vehicles that operate on public roadways.

Connected and Autonomous Vehicles

Connected Vehicles

Connected vehicles are vehicles with the capability of identifying threats and hazards on the roadway and communicating this information over wireless networks to other vehicles as well as the traffic management center to give drivers alerts and warnings. Connected vehicles use advanced wireless communications, onboard computer processing, advanced vehicle sensors, GPS navigation, and smart infrastructure, among other technologies. The connected vehicle concept is still evolving and has not yet been put into widespread practice in the United States. Current understanding of the concept suggests that connected vehicles should improve the speed of detection and response to congestion-causing incidents and reduce crashes, thereby improving travel time reliability (*5*).

Autonomous Vehicles

Autonomous vehicles are self-driving vehicles. They are distinct from connected vehicles in that autonomous vehicles cut the driver out of the routine driving process—either through assisted automation, under which the driver can choose to use automated control of specific features, or through full automation, with no control by the driver under normal circumstances. The vehicles can detect their environment and navigate their way through that environment. A few states have established laws and regulations for testing of autonomous vehicles on public streets by manufacturers. Autonomous vehicles could reduce reaction times and enable closer car following distances, which would facilitate higher densities of traffic and potentially higher capacities. They may also improve travel time reliability by reducing crashes (*6*).

Driver Characteristics (Human Factors)

Driving is a complex task involving a variety of skills. The most important skills are taking in and processing information and making quick decisions on the basis of this information. Driver tasks are grouped into three main categories: control, guidance, and navigation. Control involves the driver's interaction with the vehicle in terms of speed and direction (accelerating, braking, and steering). Guidance refers to maintaining a safe path and keeping the vehicle in the proper lane. Navigation means planning and executing a trip.

The way in which drivers perceive and process information is important. About 90% of information is presented to drivers visually. The speed at which drivers process information is significant in their successful use of the information. One parameter used to quantify the speed at which drivers process information is perception–reaction time, which represents how quickly drivers can respond to an emergency situation. Another parameter—sight distance—is directly associated with reaction time. There are three types of sight distance: stopping, passing, and decision. Sight distance helps determine appropriate geometric features of transportation facilities. Acceptance of gaps in traffic streams is associated with driver perception and influences the capacity and delay of movements at unsignalized intersections.

Factors such as nighttime driving, fatigue, distracted driving (e.g., using a mobile phone or in-vehicle technology), driving under the influence of alcohol and drugs, the age and health of drivers, and police enforcement also contribute to driver behavior on a transportation facility. All these factors can affect the operational parameters of speed, delay, and density. However, unless otherwise specified, HCM methods assume base conditions of daylight, dry pavement, typical drivers, and so forth as a starting point for analyses.

Base conditions are discussed generally in Chapter 4 and specifically in chapters in Volumes 2 and 3.

VARIATIONS IN DEMAND

The traffic volume counted at a given location on a given day is not necessarily reflective of the amount of traffic (*a*) that would be counted on another day or (*b*) that would be counted if an upstream bottleneck was removed. Traffic demand varies seasonally, by day of the week (e.g., weekdays versus weekends), and by hour of the day, as trip purposes and the number of persons desiring to travel fluctuate. Bottlenecks—locations where the capacity provided is insufficient to meet the demand over a given period of time—constrain the observed volume to the portion of the demand that can be served by the bottleneck. Because traffic counts only provide the portion of the demand that was served, the actual demand can be difficult to identify.

Demand relates to the number of vehicles that would like to be served by a roadway element, while volume relates to the number that are actually served.

The following sections discuss monthly, daily, and hourly variations in traffic demand. Analysts need to account for these types of variations to ensure that the peak-hour demand volumes used in an HCM analysis reflect conditions on peak days of the year. Failure to account for these variations can result in an analysis that reflects peak conditions on the days counts were made, but not peak conditions over the course of the year. For example, a highway serving a beach resort area may be virtually unused during much of the year but become oversaturated during the peak summer periods.

Seasonal peaks in traffic demand must also be considered, particularly on recreational facilities.

A roadway's capacity may be greater than its hourly demand, yet traffic flow may still break down if the flow rate within a portion of the hour exceeds the roadway's capacity. The effects of a breakdown can extend far beyond the time during which demand exceeded capacity and may take several hours to dissipate. Subhourly variations in demand and their effects on traffic flow are discussed in Chapter 4, Traffic Operations and Capacity Concepts.

A highway that is barely able to handle a peak-hour demand may be subject to breakdown if flow rates within a portion of the peak hour exceed capacity—a topic of Chapter 4.

The data shown in the exhibits in this section represent typical observations that can be made. However, the patterns illustrated vary in response to local travel habits and environments, and these examples should not be used as a substitute for locally obtained data.

Data shown in these graphs represent typical observations but should not be used as a substitute for local data.

Seasonal and Monthly Variations

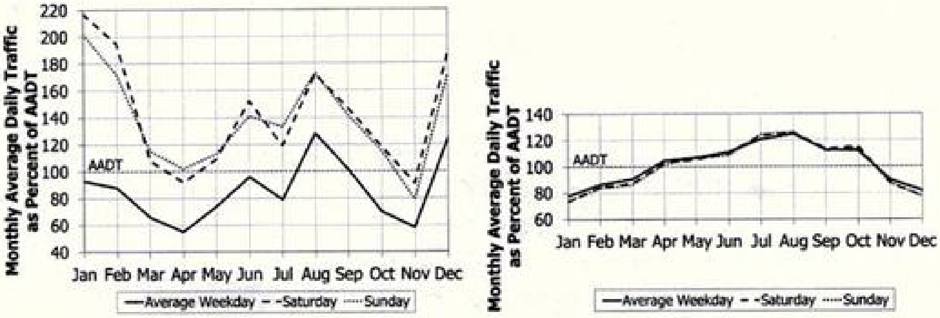
Seasonal fluctuations in traffic demand reflect the social and economic activity of the area served by the highway. Exhibit 3-2 shows monthly patterns observed in Oregon and Washington. The highway depicted in Exhibit 3-2(a) serves national forestland with both winter and summer recreational activity. The highway depicted in Exhibit 3-2(b) is a rural route serving intercity traffic. Two significant characteristics are apparent from this data set:

- The range of variation in traffic demand over the course of a year is more severe on rural routes primarily serving recreational traffic than on rural routes primarily serving intercity traffic.
- Traffic patterns vary more severely by month on recreational routes.

Exhibit 3-2
Examples of Monthly Traffic Volume Variations for a Highway

Monthly volume variations for routes with recreational traffic show much higher seasonal peaking than for routes with predominantly intercity traffic.

The average daily traffic averaged over a full year is referred to as the annual average daily traffic, or AADT, and is often used in forecasting and planning.



(a) Routes with Significant Recreational Traffic (b) Routes with Significant Intercity Traffic

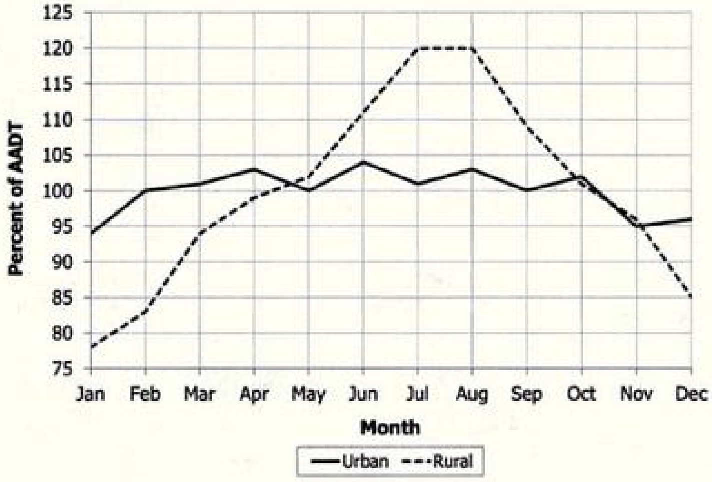
Source: (a) Oregon DOT, 2007; (b) Washington State DOT, 2007.
Notes: (a) Highway 35 south of Parkdale, Oregon; (b) US-97 north of Wenatchee, Washington.

These and similar observations lead to the conclusion that commuter- and business-oriented travel occurs in fairly uniform patterns, while recreational traffic creates the greatest variation in demand patterns.

The data for Exhibit 3-3 were collected on the same Interstate route. One segment is within 1 mi of the central business district of a large metropolitan area. The other segment is within 75 mi of the first but serves a combination of recreational and intercity travel. This exhibit illustrates that monthly variations in volume are more severe on rural routes than on urban routes. The wide variation in seasonal patterns for the two segments underscores the effect of trip purpose and may reflect capacity restrictions on the urban section.

Exhibit 3-3
Examples of Monthly Traffic Volume Variations for the Same Interstate Highway (Rural and Urban Segments)

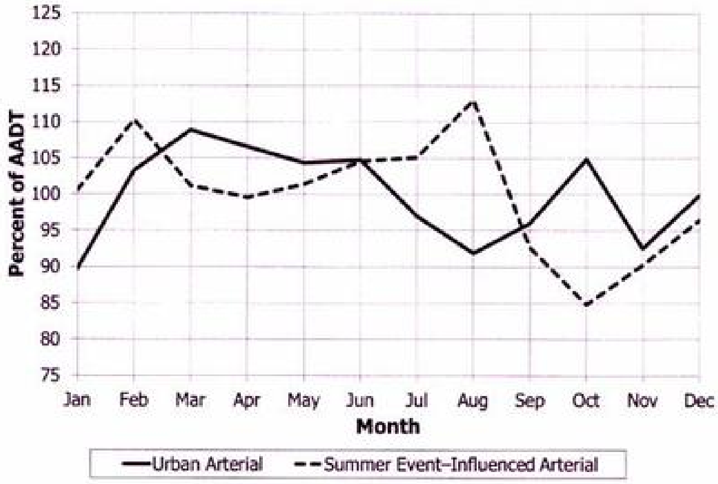
Monthly volume variations for rural segments of Interstate highways show much higher seasonal peaking than for urban segments of the same highway. This may reflect both recreational and agricultural traffic impacts.



Source: Oregon DOT, 2006.
Note: Urban, I-84 east of I-5 in Portland; rural, I-84 at Rowena.

Exhibit 3-4 shows examples of monthly traffic volume variations on two urban streets in the same large city. Comparison of these variations with those of Exhibit 3-2 and Exhibit 3-3 indicates that urban streets tend to show more month-to-month variation than urban freeways, but less variation than rural roadways. Traffic on typical urban arterials tends to drop during summer months when school is not in session, but special event (e.g., summer festival) traffic can result in higher-than-average traffic volumes during the summer.

Exhibit 3-4
Examples of Monthly Traffic Volume Variations on Urban Streets



Source: City of Milwaukee, Wisconsin, 2014.
Note: Monthly values are weekly average counts for 1 week of each month.

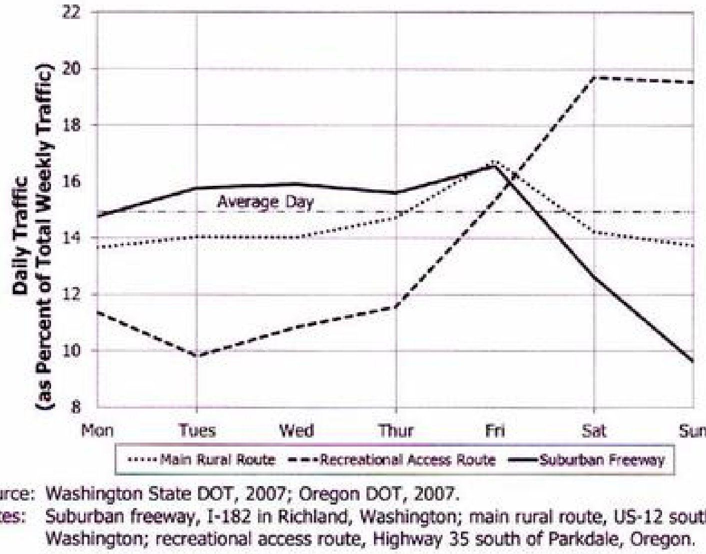
Daily Variations

Time of peak demand will vary according to highway type.

Demand variations by day of the week are also related to the type of highway. Exhibit 3-5 shows that weekend volumes are lower than weekday volumes for highways serving predominantly business travel, such as urban freeways. In comparison, peak traffic typically occurs on weekends on main rural and recreational highways. Furthermore, the magnitude of daily variation is highest for recreational access routes and lowest for urban commuter routes.

Exhibit 3-5
Examples of Daily Traffic Variation by Type of Route

Daily volume variations through the week show higher weekday volumes and lower weekend volumes for routes primarily serving commuter and intercity traffic, but the opposite for segments serving recreational traffic. Fridays are typically the peak weekday.

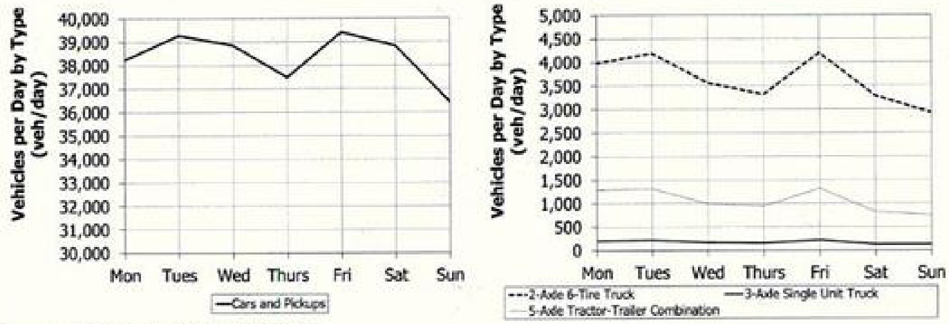


Source: Washington State DOT, 2007; Oregon DOT, 2007.
Notes: Suburban freeway, I-182 in Richland, Washington; main rural route, US-12 southeast of Pasco, Washington; recreational access route, Highway 35 south of Parkdale, Oregon.

Exhibit 3-6 shows the variation in traffic by vehicle type for the right lane of an urban freeway. Although the values shown in Exhibit 3-5 and Exhibit 3-6 are typical of patterns that may be observed, they should not be used as a substitute for local studies and analyses.

Exhibit 3-6
Daily Variation in Traffic by Vehicle Type for the Right Lane of an Urban Freeway

Daily volume variations by vehicle type through the week show higher weekday volumes and lower weekend volumes for truck traffic, with much sharper drops on the weekend for heavy truck traffic then for single-unit trucks. Car and pickup traffic peaks on Fridays and declines on weekends on this urban freeway.



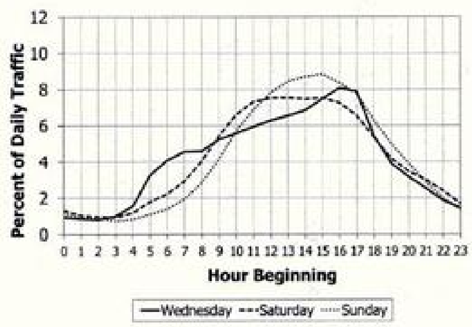
Source: Washington State DOT, 2007.
Note: Northbound Highway 16 north of I-5, Tacoma, Washington.

Hourly Variations

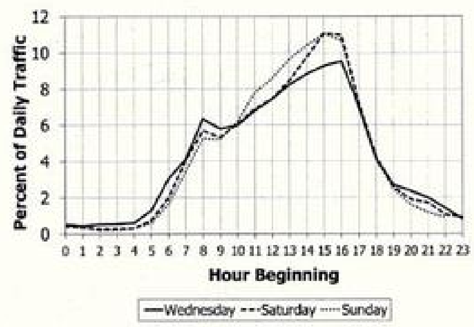
Typical hourly variation patterns for rural routes are shown in Exhibit 3-7, where the patterns are related to highway type and day of the week. Unlike urban routes, rural routes tend to have a single peak that occurs in the afternoon. A small morning peak is visible on weekdays that is much lower than the afternoon peak. The proportion of daily traffic occurring in the peak hour is much higher for recreational access routes than for intercity or local rural routes. The weekend pattern for recreational routes is similar to the weekday pattern, as travelers tend to go to their recreation destination in the morning and return in the later afternoon. Weekend morning travel is considerably lower than weekday morning travel for the other types of rural routes.

Exhibit 3-7
Examples of Hourly Traffic Variations for Rural Routes

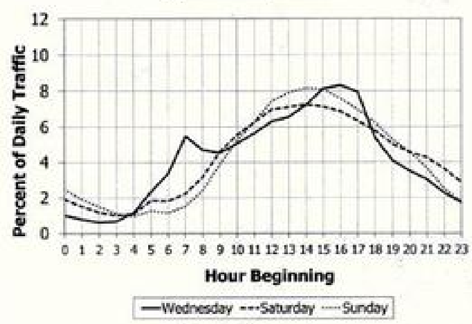
Bidirectional traffic variation during the day by day of week for rural routes.



(a) Intercity Route



(b) Recreational Access Route

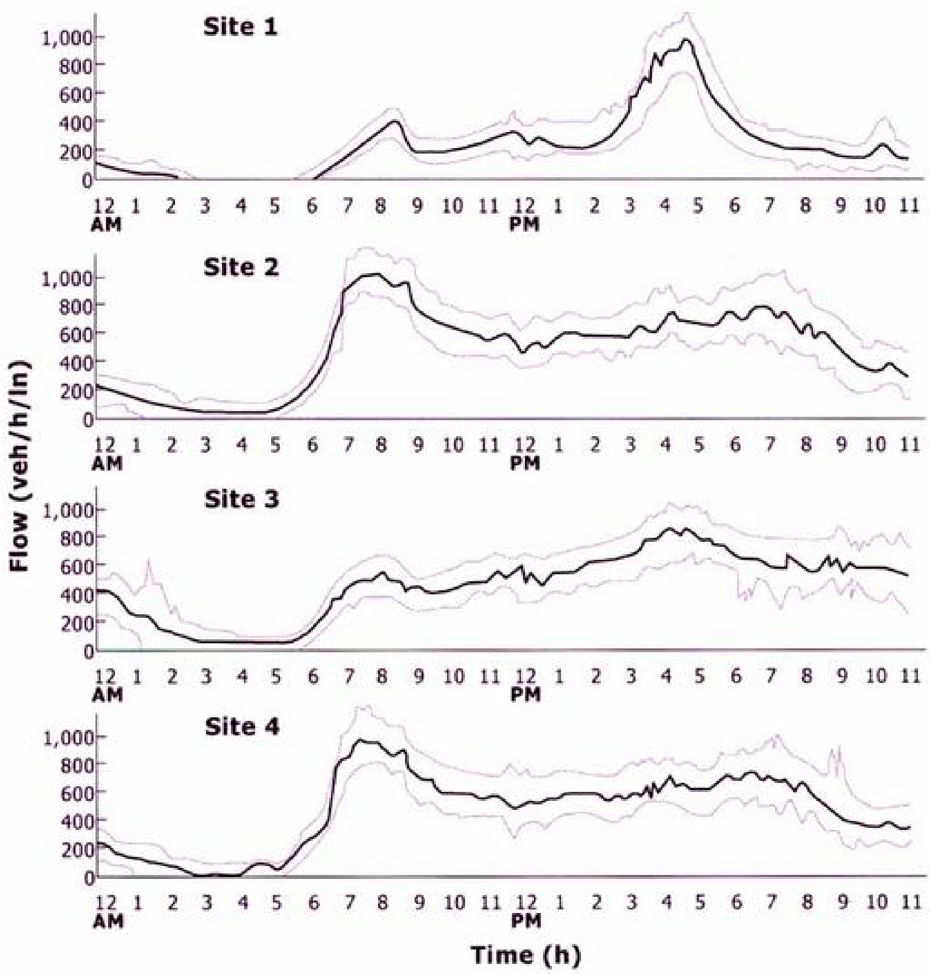


(c) Local Route

Sources: Washington State DOT, 2007; Oregon DOT, 2007.
Notes: (a) US-395 south of Kennewick, Washington; (b) Highway 35 south of Parkdale, Oregon; (c) US-97 near Wapato, Washington.

The repeatability of hourly variations is of great importance. The stability of peak-hour demand affects the feasibility of using such values in design and operational analyses of highways and other transportation facilities. Exhibit 3-8 shows data obtained for single directions of urban streets in the Toronto, Canada, region. The data were obtained from detectors measuring traffic in one direction only, as evidenced by the single peak period shown for either morning or afternoon. The area between the dotted lines indicates the range within which 95% of the observations can be expected to fall. Whereas the variations by hour of the day are typical for urban areas, the relatively narrow and parallel fluctuations among the days of the study indicate the repeatability of the basic pattern.

Exhibit 3-8
Repeatability of Hourly Traffic Variations for Urban Streets



Source: McShane and Crowley (7).

Notes: Sites 2 and 4 are one block apart on the same street, in the same direction. All sites are two moving lanes in one direction. Dotted lines indicate the range in which 95% of the observed volumes fall.

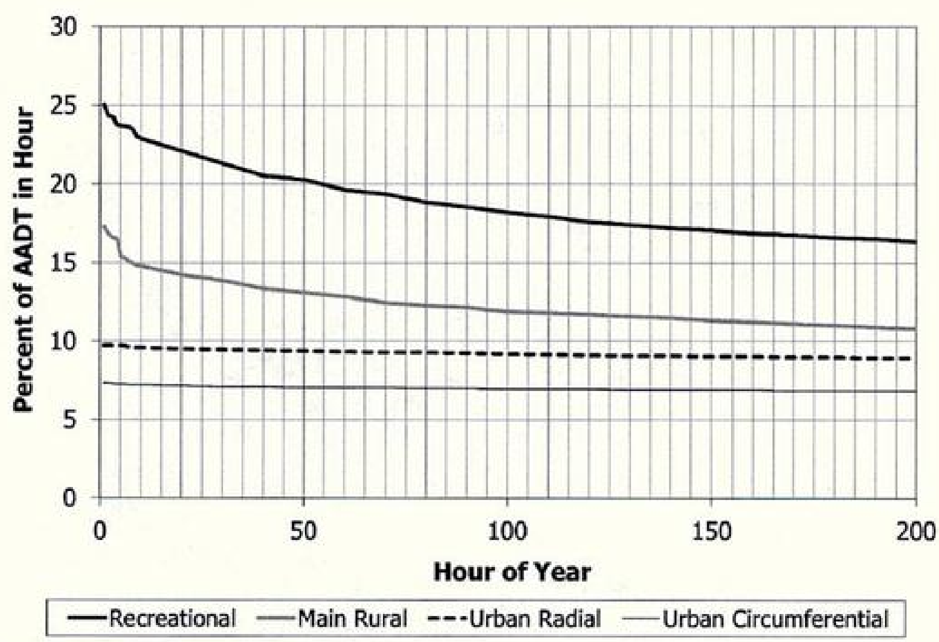
Peak Hour and Analysis Hour

Capacity and other traffic analyses typically focus on the peak-hour traffic volume because it represents the most critical period for operations and has the highest capacity requirements. However, as shown in the previous sections, the peak-hour volume is not a constant value from day to day or from season to season. If the highest hourly volumes for a given location were listed in descending order, the data would vary greatly, depending on the type of facility.

Rural and recreational routes often show a wide variation in peak-hour volumes. Several extremely high volumes occur on a few select weekends or in other peak periods, and traffic during the rest of the year flows at much lower volumes, even during the peak hour. Urban streets, on the other hand, show less variation in peak-hour traffic. Most users are daily commuters or frequent users, and occasional and special event traffic is minimal. Furthermore, many urban routes are filled to capacity during each peak hour, and variation is therefore severely constrained—an issue that will be revisited later in this section.

Exhibit 3-9 shows hourly volume relationships measured on four highway types in Washington. The recreational highway shows the widest variation in peak-hour traffic. Its values range from 25% of AADT in the highest hour of the year to about 16.3% of AADT in the 200th-highest hour of the year. The main rural freeway also varies widely, with 17.3% of the AADT in the highest hour, decreasing to 10.8% in the 200th-highest hour. The urban freeways show far less variation. The range in percent of AADT covers a narrow band, from approximately 9.7% (radial freeway) and 7.3% (circumferential freeway) for the highest hour to 8.9% and 6.9%, respectively, for the 200th-highest hour. Exhibit 3-9 is based on all hours of the year, not just peak hours of each day, and shows only the highest 200 hours of the year.

Exhibit 3-9
Ranked Hourly Volumes



Source: Washington State DOT, 2006.
Notes: Recreational, US-2 near Stevens Pass (AADT = 3,862); main rural, I-90 near Moses Lake (AADT = 10,533); urban radial, I-90 in Seattle (AADT = 120,173); urban circumferential, I-405 in Bellevue (AADT = 141,550).

The selection of an appropriate hour for planning, design, and operational purposes is a compromise between providing adequate operations for every (or almost every) hour of the year and providing economic efficiency. Customary practice in the United States is to base rural highway design on the 30th-highest hour of the year. There are few hours with higher volumes than this hour, while there are many hours with volumes not much lower. In urban areas, there is usually little difference between the 30th- and 200th-highest hours of the year, because of the recurring morning and afternoon commute patterns (*8*).

Selection of an analysis hour usually implies that a small portion of the demand during a year will not be adequately served.

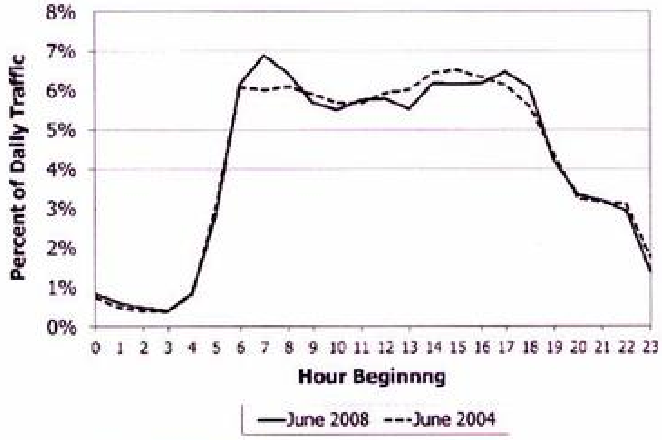
The selection of the analysis hour should consider the impact on the design and operations of higher-volume hours that are not accommodated. The recreational access route curve of Exhibit 3-9 shows that the highest hours of the year have one-third more volume than the 100th-highest hour, whereas the highest hours of an urban radial route were only about 6% higher than the volume in the 100th-highest hour. Use of a design criterion set at the 100th-highest hour would create substantial congestion on a recreational access route during the highest-volume hours but would have less effect on an urban facility. Another consideration is the LOS objective. A route designed to operate at LOS C can absorb larger amounts of additional traffic than a route designed to operate at LOS D or E during the hours of the year with higher volumes than the design hour. As a general guide, the most frequently occurring peak volumes may be considered in the design of new or upgraded facilities. The LOS during higher-volume periods should be tested to determine the acceptability of the resulting traffic conditions.

Additional analysis periods may be warranted to obtain a more robust picture of operations.

On roadways where oversaturation occurs during peak periods, analysts should be particularly careful in selecting a design hour, since measured traffic volumes may not reflect the changes in demand that occur once a bottleneck is removed. Exhibit 3-10 shows hourly variations in traffic on an urban freeway before and after the freeway was widened. In the before condition, the freeway's observed volumes were constrained by a bottleneck between 6 and 10 a.m., as indicated by the flat volume line. After the freeway widening, a more typical a.m. peak occurred, since travel patterns more closely reflected when travelers desired to travel rather than when the freeway could accommodate their travel.

Measured traffic volume patterns may not reflect actual demand patterns.

Exhibit 3-10
Example of a Change in Travel Patterns Following Removal of a Capacity Constraint



Source: Colorado DOT.
Note: I-25 south of US-6, Denver.

As used in the HCM, the *K*-factor is the proportion of AADT that occurs during the peak hour. For many rural and urban highways, this factor falls between 0.09 and 0.10. For highway sections with high peak periods and relatively low off-peak flows, the *K*-factor may exceed 0.10. Conversely, for highways that demonstrate consistent and heavy flows for many hours of the day, the *K*-factor is likely to be lower than 0.09. In general,

- The *K*-factor decreases as the AADT on a highway increases;
- The *K*-factor decreases as development density increases; and
- The highest *K*-factors occur on recreational facilities, followed by rural, suburban, and urban facilities, in descending order.

The *K*-factor should be determined, if possible, from local data for similar facilities with similar demand characteristics.

Exhibit 3-11 demonstrates how *K*-factors decrease as AADT increases, on the basis of average data from Washington State.

Exhibit 3-11
Example *K*-Factors by AADT

AADT	Average *K*-Factor	Number of Sites Included in Average *K*-Factor: Urban	Recreational	Other Rural
0–2,500	0.151	0	6	12
2,500–5,000	0.136	1	6	8
5,000–10,000	0.118	2	2	14
10,000–20,000	0.116	1	2	15
20,000–50,000	0.107	11	5	10
50,000–100,000	0.091	14	0	4
100,000–200,000	0.082	11	0	0
>200,000	0.067	2	0	0

Source: Washington State DOT (*9*).
Note: *K*-factors are for the 30th-highest traffic volume hour of the year.

Spatial Distributions

Traffic volume varies in space as well as time. The two critical spatial characteristics used in analyzing capacity are directional distribution and volume distribution by lane. Volume may also vary longitudinally along various segments of a facility. HCM methods incorporate this variation by breaking facilities into new segments at points where demand changes significantly; the operation of each segment is analyzed separately.

D-*Factor*

Concept of D*-factor or directional distribution.*

The *D*-factor is the proportion of traffic moving in the peak direction of travel on a given roadway during the peak hours. A radial route serving strong directional demands into a city in the morning and out at night may display a 2:1 imbalance in directional flows. Recreational and rural routes may also be subject to significant directional imbalances, which must be considered in analyses. Circumferential routes and routes connecting two major cities within a metropolitan area may have balanced flows during peak hours. Exhibit 3-12 provides examples of directional distributions from selected California freeways.

Exhibit 3-12
Example Directional Distribution Characteristics

Freeway Type	*D*-Factor
Rural–intercity	0.59
Rural–recreational and intercity	0.64
Suburban circumferential	0.52
Suburban radial	0.60
Urban radial	0.70
Intraurban	0.51

Source: California Department of Transportation, 2007.
Notes: Rural–intercity, I-5 at Willows; rural–recreational and intercity, I-80 west of Donner Summit; suburban circumferential, I-680 in Danville; suburban radial, I-80 in Pinole; urban radial, Highway 94 at I-5, San Diego; intraurban, I-880 in Hayward.

Directional distribution is an important factor in highway capacity analysis. This is particularly true for two-lane rural highways. Capacity and LOS vary substantially with directional distribution because of the interactive nature of directional flows on such facilities—the flow in one direction of travel influences flow in the other direction by affecting the number of passing opportunities. Procedures for two-lane highway analyses include explicit consideration of directional distribution.

While the consideration of directional distribution is not mandated in the analysis of multilane facilities, the distribution has a dramatic effect on both design and LOS. As indicated in Exhibit 3-12, up to two-thirds of the peak-hour traffic on urban radial routes has been observed as moving in one direction. Unfortunately, this peak occurs in one direction in the morning and in the opposite direction in the evening. Thus, both directions of the facility must have adequate capacity for the peak directional flow. This characteristic has led to the use of reversible lanes on some urban streets and highways.

Directional distribution is not a static characteristic. It changes annually, hourly, daily, and seasonally. Development in the vicinity of highway facilities often changes the directional distribution.

The *D*-factor is used with the *K*-factor to estimate the peak-hour traffic volume in the peak direction, as shown by Equation 3-1:

Equation 3-1

$$DDHV = AADT \times K \times D$$

where

$DDHV$ = directional design-hour volume (veh/h),

$AADT$ = annual average daily traffic (veh/day),

K = proportion of $AADT$ occurring in the peak hour (decimal), and

D = proportion of peak-hour traffic in the peak direction (decimal).

Lane Distribution

Concept of lane distribution.

When two or more lanes are available for traffic in a single direction, the lane use distribution varies widely. The volume distribution by lane depends on factors such as traffic regulations, traffic composition, speed and volume, the number and location of access points, the origin–destination patterns of drivers, the development environment, and local driver habits.

Because of these factors, there are no typical lane distributions. Data indicate that the peak lane on a six-lane freeway, for example, may be the shoulder, middle, or median lane, depending on local conditions.

Exhibit 3-13 gives daily lane distribution data for various vehicle types on three selected freeways. These data are illustrative and are not intended to represent typical values.

Exhibit 3-13
Lane Distribution by Vehicle Type

Highway	Vehicle Type	Percent Distribution By Lane[a] Lane 3	Lane 2	Lane 1
Lodge Freeway, Detroit	Light[b]	32.4	38.4	29.2
	Single-unit trucks	7.7	61.5	30.8
	Combinations	8.6	2.9	88.5
	All vehicles	31.3	37.8	30.9
I-95, Connecticut Turnpike	Light[b]	24.5	40.9	34.6
	All vehicles	22.5	40.4	37.1
I-4, Orlando, Florida	All vehicles	38.4	31.7	29.9

Sources: Huber and Tracy (*10*); Florida DOT, 1993.
Notes: [a] Lane 1 = shoulder lane; lanes numbered from right to left.
[b] Passenger cars, panel trucks, and pickup trucks.

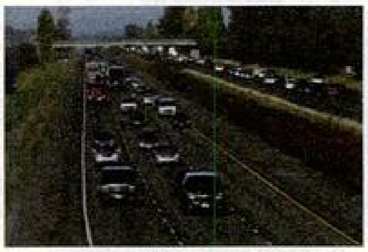
The trend indicated in Exhibit 3-13 is reasonably consistent throughout North America. Heavier vehicles tend to use the right-hand lanes, partially because they operate at lower speeds than other vehicles and partially because regulations may prohibit them from using the leftmost lanes.

Lane distribution must also be considered at intersections and interchanges. It affects how efficiently the demand for a particular movement can be served, as well as lane-by-lane queue lengths. Uneven lane distributions can be a result of upstream or downstream changes in the number of lanes available and the pre-positioning of traffic for downstream turning movements.

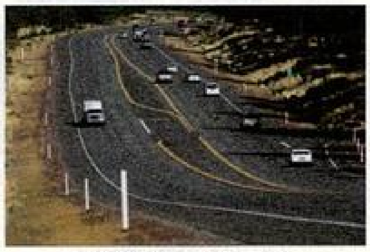
MOTORIZED VEHICLE FACILITY TYPES

Exhibit 3-14 illustrates the kinds of motorized vehicle facilities addressed in the HCM. They are divided into two main categories: *uninterrupted-flow facilities,* where traffic has no fixed causes of delay or interruption beyond the traffic stream, and *interrupted-flow facilities,* where traffic controls such as traffic signals and STOP signs introduce delay into the traffic stream.

Exhibit 3-14
Motorized Vehicle Facility Types

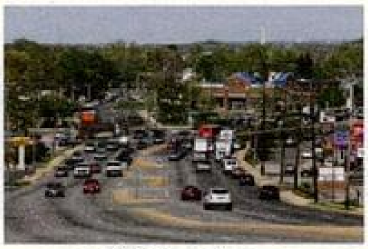


(a) Freeway



(b) Multilane Highway

(c) Two-Lane Highway



(d) Urban Street

Uninterrupted Flow

Freeways are fully access-controlled, divided highways with a minimum of two lanes (and frequently more) in each direction. Certain lanes on freeways may be reserved for designated types of vehicles, such as high-occupancy vehicles or trucks. Some freeway facilities charge tolls, and their toll-collection facilities can create interrupted-flow conditions, such as on facilities where tolls are paid manually at toll plazas located on the freeway mainline. *Ramps* provide access to, from, and between freeways; some ramps have meters that control the flow of traffic onto a freeway segment.

Multilane highways are higher-speed roadways with a minimum of two lanes in each direction. They have zero or partial control of access. Traffic signals or roundabouts may create periodic interruptions to flow along an otherwise uninterrupted facility, but such interruptions are spaced at least 2 mi apart.

Two-lane highways generally have a two-lane cross section, although passing and climbing lanes may be provided periodically. Within the two-lane sections, passing maneuvers must be made in the opposing lane. Traffic signals, STOP-controlled intersections, or roundabouts may occasionally interrupt flow, but at intervals longer than 2 mi.

Interrupted Flow

Urban streets are streets with relatively high densities of driveway and cross-street access, located within urban areas. The traffic flow of urban streets is interrupted (i.e., traffic signals, all-way stops, or roundabouts) at intervals of 2 mi or less. HCM procedures are applicable to arterial and collector urban streets, including those in downtown areas.

EFFECTS OF OTHER MODES

Each mode that uses a roadway interacts with the other modal users of that roadway. This section examines the operational effects of other modes on automobiles; the effects of automobiles on other modes are discussed later in the portions of the chapter addressing those modes. In addition to the specific interactions discussed below, changes in the amount of roadway space allocated to particular travel modes and changes in the volume of users of a given mode will affect the operations and quality of service of all the modes using the roadway, with different modes being affected in different ways.

Pedestrians

Pedestrians interact with automobiles on interrupted-flow elements of the roadway system. At signalized intersections, the minimum green time provided for an intersection approach is influenced by the need to provide adequate time for pedestrians using the parallel crosswalk to cross the roadway safely. In turn, the green time allocated to a particular vehicular movement affects the capacity of and the delay experienced by that movement. At signalized and unsignalized intersections, turning vehicles must yield to pedestrians in crosswalks, which reduces the capacity of and increases the delay experienced by those turning movements, compared with a situation in which pedestrians are not present. The increased delays at intersections and midblock pedestrian crossings along urban streets that result from higher pedestrian crossing volumes lower vehicular speeds along the urban street.

Bicycles

At intersections, motorized vehicle capacity and delay are affected by bicycle volumes, particularly where turning vehicles conflict with through bicycle movements. However, HCM methodologies only account for these effects at signalized intersections. Bicycles may also delay motorized vehicles on two-lane roadways in cases where bicycles use the travel lane, causing vehicles to wait for a safe opportunity to pass. This kind of delay is not accounted for in the HCM two-lane roadway methodology, which only addresses delays associated with waiting to pass other motorized vehicles.

Trucks and Transit

Trucks and transit vehicles are longer than passenger cars and have different performance characteristics; thus, they are treated as heavy vehicles for all types of roadway elements. At intersections, buses or streetcars that stop in the vehicular travel lane to serve passengers delay other vehicles in the lane and reduce the lane's capacity; however, this effect is only incorporated into the signalized intersection methodology. Special transit phases or bus signal priority measures at signalized intersections affect the allocation of green time to the various traffic movements, with accompanying effects on vehicular capacity and delay. To accommodate truck and bus turning radii at intersections, stop bars may need to be set back from the intersection. This in turn affects the time required for vehicles on those approaches to pass through the intersection and thus the traffic signal's change and clearance intervals, all of which affect approach and intersection capacity.

3. TRUCK MODE

OVERVIEW

Trucks with a gross vehicle weight rating (GVWR) in excess of 10,000 lb account for approximately 3% of vehicles in use on highways in the United States and accumulate about 7% of all vehicle miles traveled. They are involved in 8% of all fatal crashes and 3% of all crashes (*11*).

This chapter describes the characteristics of trucks that set them apart from other motorized vehicles. Much of the material in this chapter was developed by a National Cooperative Freight Research Program project (*1*).

TRUCK CHARACTERISTICS

The HCM defines trucks as a subclass of heavy vehicles, with heavy vehicles being defined as any vehicle with more than four tires touching the ground, regardless of the number of axles. The other two subclasses of heavy vehicles within the HCM analysis framework are buses and recreational vehicles, primarily people-hauling vehicles. Trucks are the subclass of HCM heavy vehicles dedicated primarily to moving goods, equipment, or waste. Heavy vehicles mainly involved in construction or maintenance are also defined as trucks.

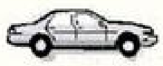
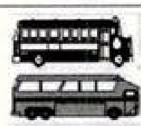
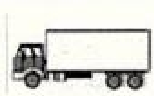
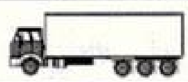
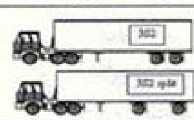
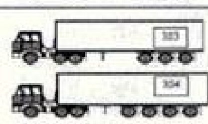
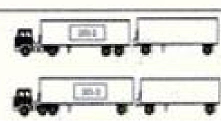
The Federal Highway Administration (FHWA) classifies all larger vehicles by the number of axles. FHWA divides two-axle vehicles into motorcycles, passenger cars, buses, and single-unit trucks, with single-unit trucks being further split into four-tire and six-tire (dual rear wheel) vehicles (see Exhibit 3-15). HCM trucks fall into FHWA Vehicle Classes 5–13. HCM buses fall into FHWA Class 4. HCM passenger cars fall into FHWA Classes 1–3.

The lengths, acceleration characteristics, and deceleration (braking) characteristics of trucks are different from those of passenger cars, which affects the amount of road capacity used by trucks. Length affects the amount of road space occupied by the truck in comparison with a passenger car. Acceleration and deceleration characteristics affect trucks' safe vehicle following distances on level, uphill, and downhill grades. They also affect trucks' maximum safe downhill speed and maximum sustainable uphill speed (*crawl speed*) on extended upgrades.

Exhibit 3-16 shows a selection of representative truck characteristics by FHWA vehicle class, derived from freeway weigh-in-motion data from Florida. Exhibit 3-17 shows how truck types are distributed by vehicle class for urban and rural freeways and multilane highways in Florida. Variations in truck percentages among facility and area types can be substantial. The percentages can also vary by time of day (*14*), although that is not shown in the exhibit.

Exhibit 3-18 shows the distribution of trucks on California freeways according to their weight-to-power ratio. A truck's acceleration capabilities are tied to this ratio, as indicated in Exhibit 3-19. Generally, the higher the weight-to-power ratio, the lower the maximum acceleration rate and the lower the crawl speed.

Exhibit 3-15
FHWA Vehicle Classification Scheme

Class	Illustration	Description
1		***Motorcycles.*** All two- or three-wheeled motorized vehicles.
2		***Passenger Cars.*** All sedans, coupes, and station wagons manufactured primarily for carrying passengers and including passenger cars pulling recreational or other light trailers.
3		***Other Two-Axle, Four-Tire Single-Unit Vehicles.*** All two-axle, four-tire vehicles, other than passenger cars. Generally pickup trucks, sport-utility vehicles, and vans.
4		***Buses.*** All vehicles manufactured as traditional passenger-carrying buses with two axles and six tires or three or more axles. Excludes modified buses no longer capable of mass passenger transport.
5		***Two-Axle, Six-Tire Single-Unit Trucks.*** All vehicles on a single frame with two axles and dual rear wheels. Includes some trucks, camping and recreational vehicles, and motor homes.
6		***Three-Axle Single-Unit Trucks.*** All vehicles on a single frame with three axles. Includes some trucks, camping and recreational vehicles, and motor homes.
7		***Four or More Axle Single-Unit Trucks.*** All trucks on a single frame with four or more axles.
8		***Four or Fewer Axle Single-Trailer Trucks.*** All vehicles with four or fewer axles consisting of two units, one of which is a tractor or straight truck power unit.
9		***Five-Axle Single-Trailer* Trucks.** All five-axle vehicles consisting of two units, one of which is a tractor or straight truck power unit.
10		***Six or More Axle Single-Trailer Trucks.*** All vehicles with six or more axles consisting of two units, one of which is a tractor or straight truck power unit.
11		***Five or Fewer Axle Multitrailer Trucks.*** All vehicles with five or fewer axles consisting of three or more units, one of which is a tractor or straight truck power unit.
12		***Six-Axle Multitrailer Trucks.*** All six-axle vehicles consisting of three or more units, one of which is a tractor or straight truck power unit.
13		***Seven or More Axle Multitrailer Trucks.*** All vehicles with seven or more axles consisting of three or more units, one of which is a tractor or straight truck power unit. Includes triple-trailer combinations.

Sources: Adapted from FHWA (*12*) and Maryland State Highway Administration (*13*).
Note: FHWA Classes 1–3 are HCM passenger cars, Class 4 is HCM buses, and Classes 5–13 are HCM trucks.

Exhibit 3-16
Characteristics of Trucks by FHWA Vehicle Class (Florida)

FHWA Vehicle Class	Average Weight (lb)	Average Length (ft)	Typical Power (hp)	Typical Weight-to-Power Ratio (lb/hp)
5	14,500	29	300	48
6	30,100	30	300	100
7	65,600	28	485	135
8	37,300	59	485	77
9	53,500	69	485	110
10	62,600	73	485	129
11	54,700	75	485	113
12	56,300	78	485	116
13	87,900	95	485	181
All	44,100	--	--	--

Source: Weights and lengths derived from Washburn and Ozkul (*14*) by using all-day weigh-in-motion data for 12 freeway sites in Florida for 2008–2011. Typical power from Washburn and Ozkul (*14*).

Notes: Class 4 is buses. Class 5 includes six-tire pickup trucks and recreational vehicles, along with six-tire, four-axle single-unit trucks.

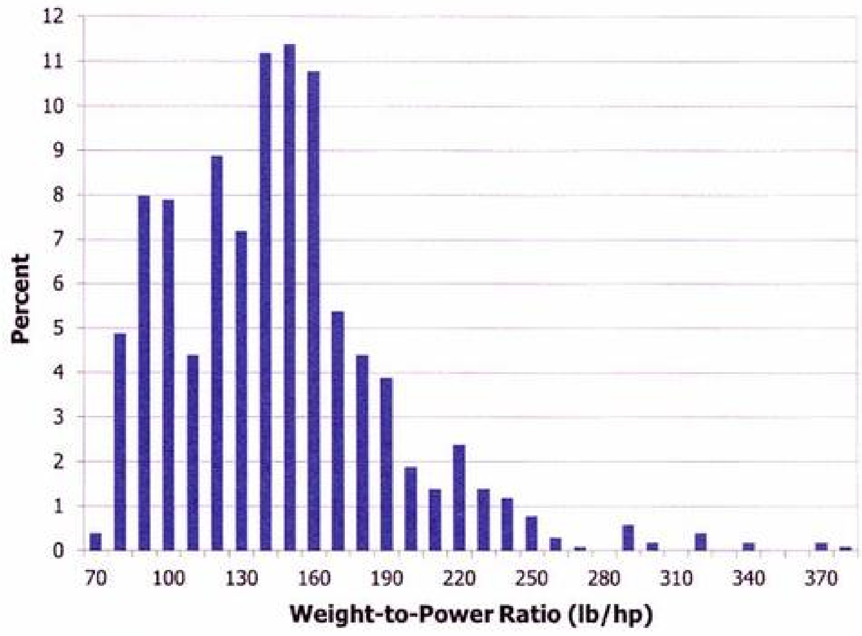
Exhibit 3-17
Percentage of Trucks by FHWA Vehicle Class (Florida)

FHWA Vehicle Class	Freeways		Multilane Highways	
	Urban	Rural	Urban	Rural
5	28.6%	17.0%	33.6%	25.8%
6	6.6%	2.6%	16.7%	4.8%
7	1.3%	0.2%	3.5%	0.5%
8	11.2%	8.0%	10.3%	10.3%
9	48.3%	66.8%	34.9%	55.7%
10	0.6%	0.6%	0.5%	0.5%
11	2.1%	2.9%	0.3%	1.3%
12	0.9%	1.8%	0.2%	0.7%
13	0.3%	0.2%	0.1%	0.4%

Source: Washburn and Ozkul (*14*), based on all-day weigh-in-motion data for 24 sites in Florida for 2008–2011.

Notes: Class 5 includes six-tire pickup trucks and recreational vehicles, along with six-tire, four-axle single-unit trucks. The percentage of Class 13 in the traffic stream will depend in part on state laws permitting longer vehicles such as triple trailers. Percentages can differ significantly by time of day.

Exhibit 3-18
Weight-to-Power Ratio Distribution Example (California)



Source: Harwood et al. (*15*).

Notes: Number of observations = 1,195, 25th percentile ratio = 112, median ratio = 141, 75th percentile ratio = 164, 85th percentile ratio = 183, 95th percentile ratio = 198.
Weight-to-power distributions are available for other states in the same report.

Exhibit 3-19
Average Truck Acceleration Rate (ft/s^2) to 40 mi/h

Weight-to-Power Ratio (lb/hp)	Starting Speed (mi/h)			
	0	**10**	**20**	**30**
100	1.87	1.70	1.47	1.29
200	1.22	1.08	0.96	0.79
300	0.91	0.81	0.72	0.58
400	0.71	0.61	0.50	0.36

Source: Harwood et al. (*15*).

The GVWR is the sum of the empty vehicle weight, fuel, and maximum safe load the vehicle can carry as certified by the manufacturer. For single-unit trucks (Classes 5–7), the GVWR ranges from 54,000 to 68,000 lb. For semitrailer combination trucks (Classes 8–13), the GVWR can range from 80,000 to 148,000 lb (*11*). The average weight of loaded and unloaded trucks is usually substantially less than the GVWR.

Highway load limits imposed by highway operating agencies affect which routes certain trucks can use. Operating agencies, at their discretion, also issue permits for oversize and overweight loads that allow one-time use (or multiple use) of a specified route for loads that exceed legal limits.

Trucks carrying certain hazardous materials and certain buses must come to a complete stop in the travel lane at each at-grade railroad crossing before proceeding, regardless of whether a train is present.

Unless the highway operating agency imposes different speed limits for trucks and passenger cars, trucks can usually move at the same speeds as passenger cars in level terrain. On long upgrades (4% or greater for 0.5 mi or more) or long downgrades (4% or greater downgrades extending for 0.5 mi or more), trucks will operate at lower speeds than passengers cars. This causes turbulence when the passenger cars attempt to pass the trucks and general reductions in overall speeds, especially when trucks pass each other on the grade.

EFFECTS OF OTHER MODES

This section examines the operational effects of other modes on the truck mode; the effects of the truck mode on other modes are discussed in the portions of the chapter addressing those modes.

Automobiles

A focus group of Canadian truck drivers with excellent driving records (*16*) found that truck drivers felt that automobile drivers were less consistent in their driving behavior than were truck drivers, which affected truck drivers' perceptions of safety. This study and a study of American truck drivers (*17*) also found that while truck drivers were concerned about travel times and maneuverability, their most important concern was their need to move at a steady speed, without much braking or changing of gears. As a result of these issues, nighttime was considered "premium truck traffic time," since trucks could travel without interference from automobiles during that time and thus have more reliable travel times (*16*).

Pedestrians

The pedestrian–automobile interactions described previously also affect truck operations. However, because of trucks' poorer acceleration capabilities, stops created by the need to yield to pedestrians have a more severe impact on truck operations than on automobile operations. In addition, trucks have longer braking distances, and therefore pedestrians' potentially unpredictable behavior is a greater concern for truck drivers (*16*).

Bicycles

The bicycle–automobile interactions described previously also affect truck operations.

Transit

Buses stopping in the travel lane on urban streets to serve passengers have a greater effect on trucks than on automobiles because of (*a*) the greater delay caused by trucks' poorer acceleration capabilities and, on multilane streets, (*b*) the larger gap in traffic that is required for trucks to change lanes to pass the bus.

4. PEDESTRIAN MODE

OVERVIEW

Approximately 10% of all trips in the United States are accomplished by walking (*18*). Moreover, many automobile trips and most transit trips include at least one section where the traveler is a pedestrian. When a network of safe and convenient pedestrian facilities is provided and potential destinations are located within walking distance of the trip origin, walking can be the mode of choice for a variety of shorter trips, including going to school, running errands, and recreational and exercise trips.

HUMAN FACTORS

Pedestrians are considerably more exposed than are motorists, in both good and bad ways. Pedestrians travel much more slowly than other modal users and can therefore pay more attention to their surroundings. The ability to take in surroundings and get exercise while doing so can be part of the enjoyment of the trip. At the same time, pedestrians interact closely with other modal users, including other pedestrians, with safety, comfort, travel hindrance, and other implications. In addition, pedestrians are exposed to the elements. As a result, a number of environmental and perceived safety factors significantly influence pedestrian quality of service. In locations with large numbers of pedestrians, pedestrian flow quality is also a consideration.

Some pedestrian flow measures are similar to those used for vehicular flow, such as the freedom to choose desired speeds and to bypass others. Others are related specifically to pedestrian flow, such as (*a*) the ability to cross a pedestrian traffic stream, to walk in the reverse direction of a major pedestrian flow, and to maneuver without conflicts or changes in walking speed and (*b*) the delay experienced by pedestrians at signalized and unsignalized intersections.

Environmental factors contribute to the walking experience and, therefore, to the quality of service perceived by pedestrians. These factors include the comfort, convenience, safety, and security of the walkway system. Comfort factors include weather protection; proximity, volume, and speed of motor vehicle traffic; pathway surface; and pedestrian amenities. Convenience factors include walking distances, intersection delays, pathway directness, grades, sidewalk ramps, wayfinding signage and maps, and other features making pedestrian travel easy and uncomplicated.

Safety is provided by separating pedestrians from vehicular traffic both horizontally, by using pedestrian zones and other vehicle-free areas, and vertically, by using overpasses and underpasses. Traffic control devices such as pedestrian signals can provide time separation of pedestrian and vehicular traffic, which improves pedestrian safety. Security features include lighting, open lines of sight, and the degree and type of street activity.

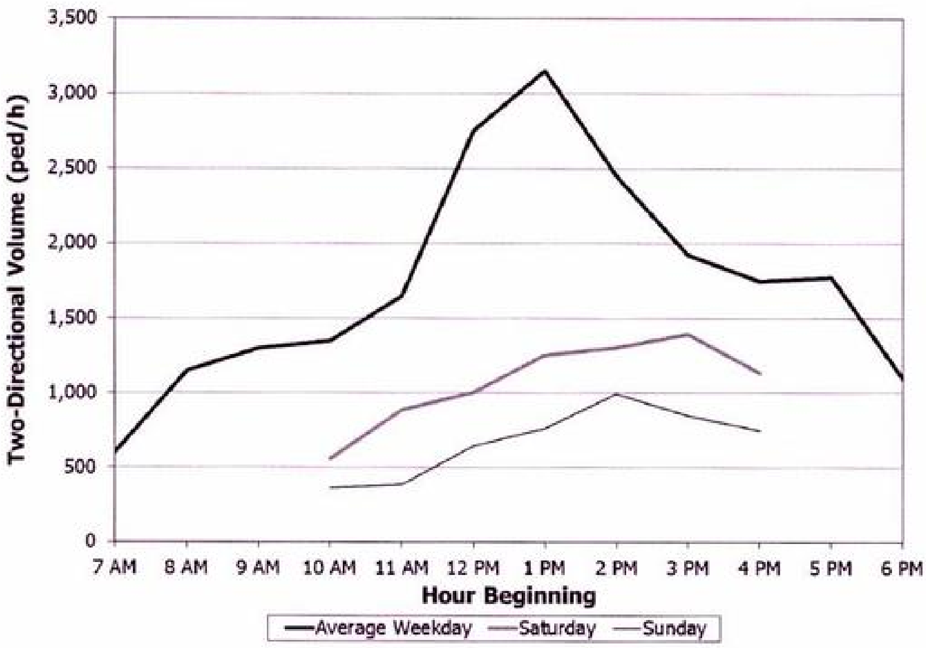
Chapter 4, Traffic Operations and Capacity Concepts, discusses pedestrian flow measures, such as speed, space, and delay, while Chapter 5, Quality and

Level-of-Service Concepts, covers the environmental factors that influence pedestrian quality of service.

VARIATIONS IN DEMAND

Pedestrian demand differs from that of the other modes addressed in the HCM in that the peak pedestrian demand often occurs at midday or during the early afternoon. Depending on the location, secondary peaks or plateaus in demand may also occur during the weekday a.m. and p.m. peak hours. Exhibit 3-20 shows two-directional pedestrian volume data collected in May 2004 on a sidewalk in Lower Manhattan, for an average of 5 weekdays in a week, Saturday, and Sunday. Although weekday demand was considerably higher than weekend demand, a single peak can be seen clearly in all three counts. Work-related trips made up the majority of a.m. peak-period pedestrian trips, while non-work-related and tourist trips made up the majority of the midday and early afternoon pedestrian trips (*19*).

Exhibit 3-20
Illustrative Temporal Variations in Pedestrian Demand

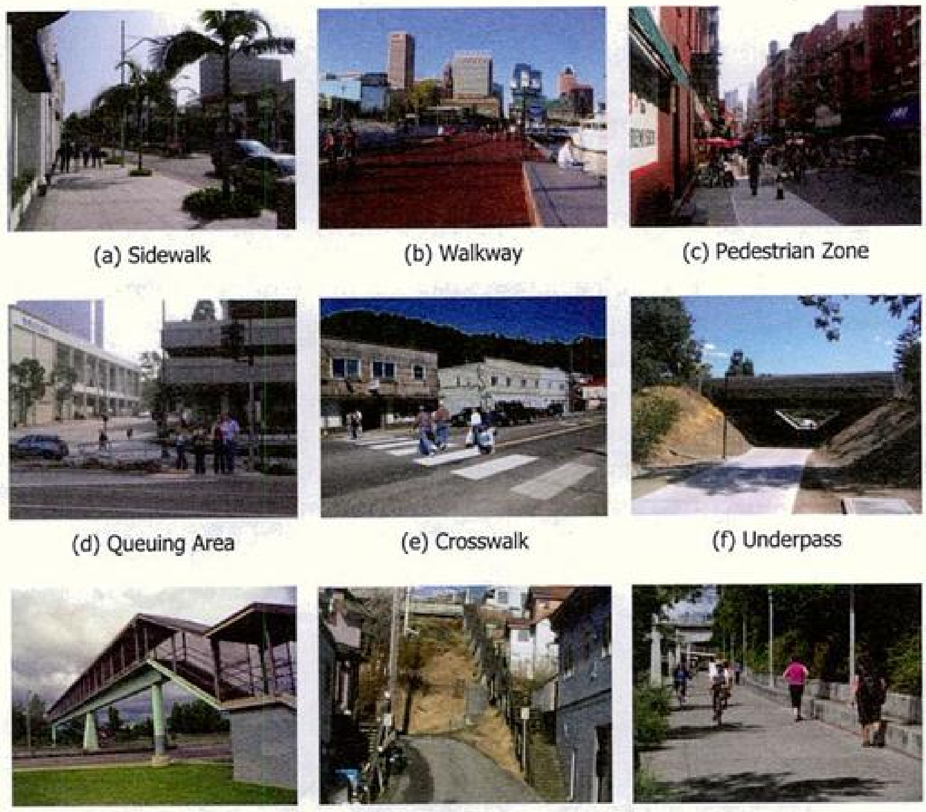


Source: Adapted from New York City Department of City Planning (*19*).

PEDESTRIAN FACILITY TYPES

Exhibit 3-21 illustrates the types of pedestrian facilities addressed in the HCM. The following sections define each type of facility.

Exhibit 3-21
Pedestrian Facility Types



(a) Sidewalk (b) Walkway (c) Pedestrian Zone
(d) Queuing Area (e) Crosswalk (f) Underpass
(g) Overpass (h) Stairway (i) Shared Pedestrian–Bicycle Path

Sidewalks, Walkways, and Pedestrian Zones

These three facility types are separated from motor vehicle traffic and typically are not designed for bicycles or other users, other than persons in wheelchairs. They accommodate higher volumes of pedestrians and provide better levels of service than do similarly sized shared-use paths, because pedestrians do not share the facility with other modes traveling at higher speeds.

Sidewalks are located parallel and in proximity to roadways. Pedestrian walkways are similar to sidewalks in construction and may be used to connect sidewalks, but they are located well away from the influence of automobile traffic. Pedestrian zones are streets that are dedicated to pedestrian use on a full- or part-time basis.

Pedestrian walkways are also used to connect portions of transit stations and terminals. Pedestrian expectations concerning speed and density in a transit context are different from those in a sidewalk context; the *Transit Capacity and Quality of Service Manual* (*20*) provides more information on this topic.

Queuing Areas

Queuing areas are places where pedestrians stand temporarily while waiting to be served, such as at the corner of a signalized intersection. In dense standing crowds, there is little room to move, and circulation opportunities are limited as the average space per pedestrian decreases.

Pedestrian Crosswalks

Pedestrian crosswalks, whether marked or unmarked, provide connections between pedestrian facilities across sections of roadway used by motorized vehicles, bicycles, and transit vehicles. Depending on the type of control used for the crosswalk, local laws, and driver observance of those laws, pedestrians will experience varying levels of delay, safety, and comfort while using the crosswalk.

Stairways

Stairways are sometimes used to help provide pedestrian connectivity in areas with steep hills, employing the public right-of-way that would otherwise contain a roadway. They are often also used in conjunction with a ramp or elevator to provide shorter access routes to overpasses, underpasses, or walkways located at a different elevation. Even a small number of pedestrians moving in the opposite direction of the primary flow can significantly decrease a stairway's capacity to serve the primary flow.

Overpasses and Underpasses

Overpasses and underpasses provide a grade-separated route for pedestrians to cross wide or high-speed roadways, railroad tracks, busways, and topographic features. Access is typically provided by a ramp or, occasionally, an elevator, which is often supplemented with stairs. Procedures exist for assessing the quality of pedestrian flow on these facilities, but not the quality of the pedestrian environment.

Shared Pedestrian–Bicycle Paths

Shared pedestrian paths typically are open to use by nonmotorized modes such as bicycles, skateboards, and inline skaters. Shared-use paths often are constructed to serve areas without city streets and to provide recreational opportunities for the public. They are common on university campuses, where motor vehicle traffic and parking are often restricted. In the United States, there are few paths exclusively for pedestrians; most off-street paths, therefore, are for shared use.

On shared facilities, bicycles—because of their markedly higher speeds—can negatively affect pedestrian capacity and quality of service. However, it is difficult to establish a bicycle–pedestrian equivalent because the relationship between the two depends on the characteristics of the cycling population, the modes' respective flows and directional splits, and other factors.

EFFECTS OF OTHER MODES

Automobiles and Trucks

At signalized intersections, the delay experienced by pedestrians is influenced by the amount of green time allocated to serve vehicular volumes on the street being crossed. The volume of motorized vehicles making turns across a crosswalk at an intersection also affects a pedestrian's delay and perception of the intersection's quality of service.

At unsignalized intersections, increased major-street traffic volumes affect pedestrian crossing delay by reducing the number of opportunities for pedestrians to cross. The effect of motorized vehicle volumes on pedestrian delay at unsignalized intersections also depends on local laws specifying yielding requirements to pedestrians in crosswalks and driver observation of those laws.

Automobile and heavy vehicle traffic volumes and the extent to which pedestrians are separated from vehicular traffic influence pedestrians' perceptions of quality of service while walking along a roadway.

Large intersection corner turning radii required to accommodate turning heavy vehicles increase pedestrian crossing distances, which increases pedestrian exposure, as well as the length of the pedestrian clearance interval for the affected crosswalks. The latter factor influences the approach and intersection capacity.

Bicycles

Bicycle interaction with pedestrians is greatest on pathways shared by the two modes. Bicycles—because of their markedly higher speeds—can negatively affect pedestrian capacity and quality of service on such pathways.

Transit

The interaction of transit vehicles with pedestrians is similar to that of automobiles. However, because transit vehicles are larger than automobiles, the effect of a single transit vehicle is proportionately greater than that of a single automobile. The lack of pedestrian facilities in the vicinity of transit stops can be a barrier to transit access, and transit quality of service is influenced by the quality of the pedestrian environment along streets with transit service. Although it is not addressed by the HCM procedures, the pedestrian environment along the streets used to get to and from the streets with transit service also influences transit quality of service. Passengers waiting for buses at a bus stop can reduce the effective width of a sidewalk, while passengers getting off buses may create cross flows that interact with the flow of pedestrians along a sidewalk.

5. BICYCLE MODE

OVERVIEW

Bicycles are used to make a variety of trips, including trips for recreation and exercise, commutes to work and school, and trips for errands and visiting friends. Bicycles help extend the market area of transit service, since bicyclists can travel about five times as far as an average person can walk in the same amount of time. Although bicycle trip making in North America is lower than in other parts of the world, several large North American cities that have invested in bicycle infrastructure and programs (e.g., Portland, Oregon; Minneapolis, Minnesota; Seattle, Washington; Washington, D.C.; and Vancouver, Canada) have bicycle commute mode splits between 4% and 6% (2012 census and local data). Some college towns have even higher commute mode splits, such as Eugene, Oregon (8%); Boulder, Colorado (12%); and Davis, California (19%), according to 2012 census data.

HUMAN FACTORS

Many of the measures of vehicular effectiveness can also describe bicycling conditions, whether on exclusive or shared facilities. As with motor vehicles, bicycle speeds remain relatively insensitive to flow rates over a wide range of flows. Delays due to traffic control affect bicycle speeds along a facility, and the additional effort required to accelerate from a stop is particularly noticeable to bicyclists. Grades, bicycle gearing, and the bicyclist's fitness level also affect bicycle speed and the level of effort required to maintain a particular speed.

Electric and electric assist bicycles are gaining popularity. They help address concerns such as accelerating from a stop and climbing up hills that affect human-powered bicycles.

Some vehicular measures are less applicable to the bicycle mode. For example, bicycle density is difficult to assess, particularly with regard to facilities shared with pedestrians and others. Because of the severe deterioration of service quality at flow levels well below capacity (e.g., freedom to maneuver around other bicyclists), the concept of capacity has little utility in the design and analysis of bicycle paths and other facilities. Capacity is rarely observed on bicycle facilities. Values for capacity therefore reflect sparse data, generally from European studies or from simulation.

Hindrance as a bicycle-specific performance measure.

Other measures of bicycle quality of service have no vehicular counterpart. For example, the concept of hindrance relates directly to bicyclists' comfort and convenience (*21*). During travel on a bicycle facility, bicyclists meet other pathway users in the opposite direction and overtake pathway users moving in the same direction. Each meeting or passing event can cause discomfort, delay, or both (hindrance) to the bicyclist.

As is the case with pedestrians, environmental factors contribute significantly to the bicycling experience and, therefore, to quality of service. These factors include the volume and speed of adjacent vehicles, the presence of heavy vehicles, the presence of on-street parking, the quality of the pavement, and the frequency and quality of street sweeping and snow-clearing activities. Chapter 5, Quality and Level-of-Service Concepts, discusses environmental and hindrance factors, while Chapter 4, Traffic Operations and Capacity Concepts, presents bicycle flow measures.

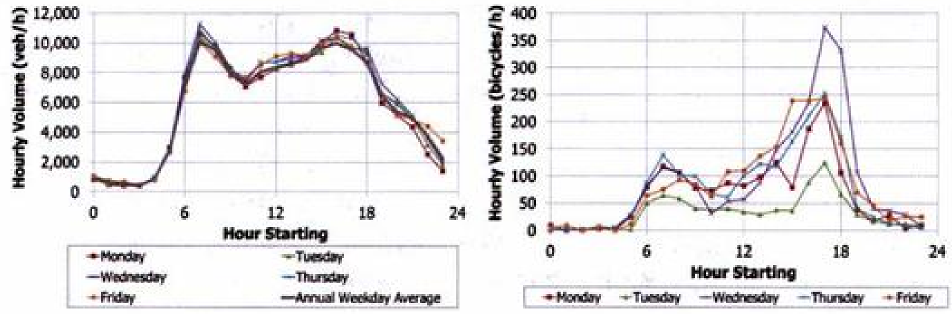
VARIATIONS IN DEMAND

Bicycle travel demand varies by time of day, day of the week, and month of the year. All of these variations are related to trip-making demands in general (e.g., bicycle commuting demand is highest during weekday a.m. and p.m. peak periods, just as with motor vehicles). However, bicyclists are more exposed than motorists to the elements and other roadway users. Dutch research shows that weather explains up to 80% of annual variation in bicycle travel, with higher rainfall and lower temperatures resulting in lower rates of bicycling (22).

The greater variability in bicycle than in automobile demand is partly due to environmental effects and partly due to the generally greater variability inherent in lower traffic volumes.

Exhibit 3-22 illustrates that bicycle demand is much more variable than is demand for motorized vehicles. The exhibit compares observed hourly bicycle volumes on a multiuse path in Minneapolis with observed hourly vehicle volumes on a parallel freeway a couple of miles away, for 1 week in October 2013. The daily freeway volumes are similar, with the p.m. peak-hour volume varying only 5% from the lowest-volume to the highest-volume day. In contrast, the bicycle volumes show 200% variability in the p.m. peak hour, a result of 1 in. of rain on Tuesday, 0.5 in. of rain on Monday and Thursday, 0.1 in. on Friday, and 0.01 in. on Wednesday. The greater variability in bicycle volumes means that longer counting periods are needed to obtain accurate bicycle demand estimates (23).

Exhibit 3-22
Illustrative Comparison of Motorized Vehicle and Bicycle Demand Variability

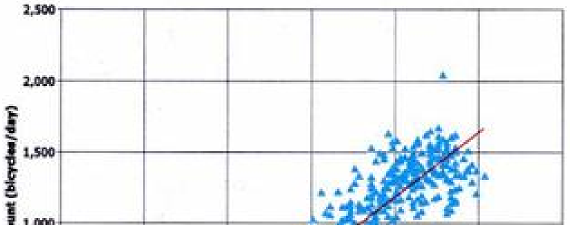


(a) Freeway (b) Multiuse Path

Source: Ryus et al. (23).
Note: (a) Freeway: I-394, Minneapolis. (b) Multiuse path: Midtown Greenway, Minneapolis.

Variations in bicycle demand are related to weather and daylight. For example, Exhibit 3-23 shows observations of bicycle demand compared with variations in daily high temperature along a bicycle path in Colorado.

Exhibit 3-23
Example Variations in Bicycle Demand due to Temperature

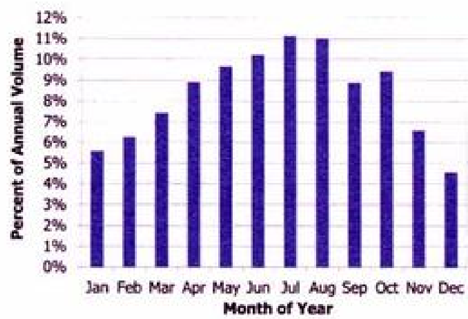


Source: Lewin (24).

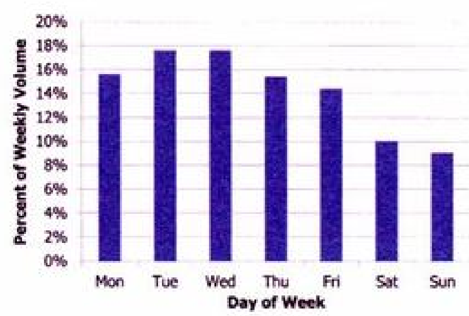
Environmental effects on bicycle demand are also apparent in Exhibit 3-24(a), which shows that the coldest and darkest months of the year have the lowest bicycle volumes. Rainfall effects can also be observed in September, when three times the normal rainfall occurred, and in October, when one-third the normal rainfall occurred. Exhibit 3-24(b) shows daily variations observed on a main bicycle commuter route. Considerable differences in volume between weekdays can be observed, and weekend demands are noticeably lower. The demand pattern observed on a recreational route would likely show higher weekend volumes relative to weekday volumes. Exhibit 3-24(c) shows hourly variations observed on the same bicycle commuter route and indicates that commuter bicycle traffic experiences a.m. and p.m. peaks.

The greater variability in bicycle volumes means that longer counting periods are needed to obtain accurate bicycle demand estimates.

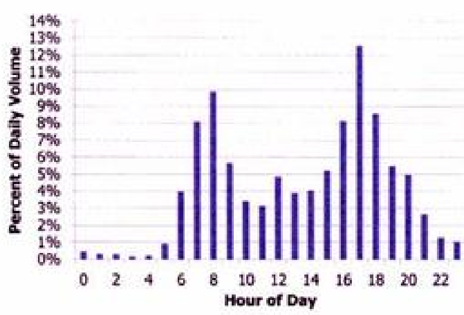
Exhibit 3-24
Illustrative Temporal Variations in Bicycle Demand



(a) Monthly Variations



(b) Daily Variations on a Commuter Route



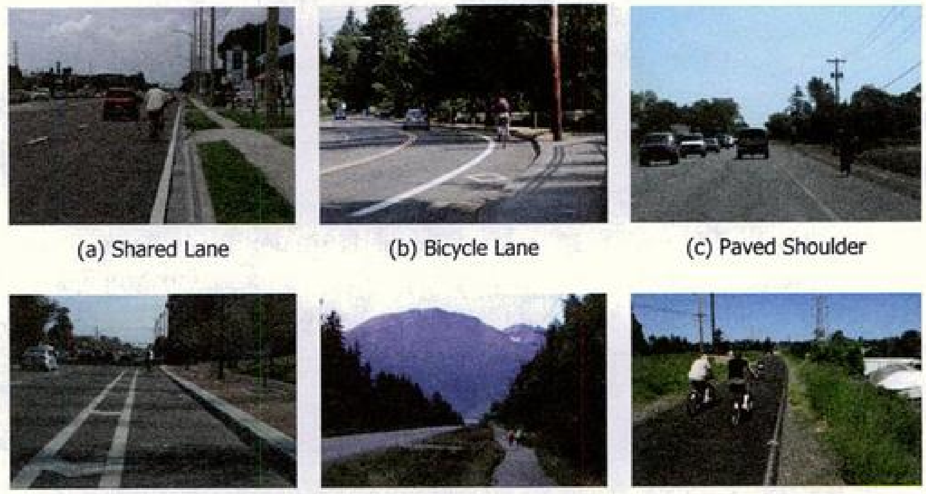
(c) Hourly Variations on a Commuter Route

Source: Portland Bureau of Transportation, Hawthorne Bridge.
Notes: (a) Data for 2013, westbound (into downtown).
(b) Data for July 8–September 8, 2013, westbound, excluding the week of August 5–11, when a bicycle event occurred that made Sunday the highest-volume day of the week.
(c) Data for 2008, including both travel directions.

BICYCLE FACILITY TYPES

Exhibit 3-25 illustrates the types of bicycle facilities addressed in the HCM. The facilities are divided into two types, on-street and off-street, and include situations in which a facility is shared with users of another mode (e.g., a lane shared by bicyclists and motor vehicle traffic or a pathway shared by bicyclists and pedestrians).

Exhibit 3-25
Bicycle Facility Types



(a) Shared Lane (b) Bicycle Lane (c) Paved Shoulder

(d) Buffered Bicycle Lane (e) Sidepath (f) Exclusive Pathway

On-Street Bicycle Facilities

On-street bicycle facilities include roadways on which bicycles share a travel lane with motorized vehicular traffic; dedicated on-street bicycle lanes; paved roadway shoulders available for use by bicyclists; and buffered bicycle lanes, where a painted island separates bicycle and motorized vehicle traffic. Bicycle flow is typically one-way, but some two-way facilities have been developed. The quality of bicycle flow, safety, and the bicycling environment are all considerations for these types of facilities.

Off-Street Bicycle Facilities

Off-street bicycle facilities consist of pathways dedicated to the exclusive use of bicyclists and pathways shared with pedestrians and other types of users. These types of facilities may be located parallel and in proximity to roadways (*sidepaths*), or they may be completely independent facilities, such as recreational trails along former railroad rights-of-way and off-street pathways of the kind found in city parks and on college campuses. Bicycle flow along these types of facilities is typically two-way and is often shared with users of other modes. The number of meeting and passing events between cyclists and other path users affects the quality of service for bicyclists using these facility types. The presence and design of driveways and intersections may affect the quality of service of bicyclists on sidepaths but is not addressed by HCM procedures.

EFFECTS OF OTHER MODES

Automobiles

Traffic volumes and speeds, the presence of on-street parking (which presents the potential for bicyclists to hit or be hit by car doors), and the degree to which bicyclists are separated from traffic all influence bicyclists' perceptions of the quality of service received during use of an on-street bicycle facility. Turning vehicles, particularly right-turning vehicles that cross the path of bicyclists, also affect quality of service.

Pedestrians

The effect of pedestrians on bicycles is greatest on pathways shared by the two modes. Pedestrians—because of their markedly lower speeds and tendency to travel in groups several abreast—can negatively affect bicycle quality of service on such pathways. Bicyclists must yield to crossing pedestrians, and the signal timing at intersections reflects, in part, the time required for pedestrians to cross the street.

Transit Vehicles and Trucks

Transit vehicles and trucks interact with bicycles in much the same way as automobiles. However, because of the greater size of these vehicles and the potential for wind blast, the effect of a single vehicle is proportionately greater than that of a single automobile. Heavy vehicle blind spots can also create safety issues when these vehicles make right turns across bicycle facilities.

Buses affect bicyclists when they pull over into a bicycle lane or paved shoulder to serve a bus stop; however, this impact is not accounted for in HCM procedures. Although not addressed by HCM procedures, the availability of good bicycle access extends the capture shed of a transit stop or station, and when bicycles can be transported by transit vehicles, transit service can greatly extend the range of a bicycle trip.

6. TRANSIT MODE

OVERVIEW

Transit plays two major roles in North America. First, it accommodates *choice* riders—those who choose transit for their mode of travel even though they have other means available. These riders choose transit to avoid congestion, save money on fuel and parking, use their travel time productively for other activities, and reduce the impact of automobile driving on the environment, among other reasons. Transit is essential for mobility in the central business districts of some major cities.

The other major role of transit is to provide basic mobility for segments of the population that are unable to drive for age, physical, mental, or financial reasons. In 2009, about 31% of Americans and Canadians did not have a driver's license (*25, 26*) and depended on others to transport them (e.g. , in automobiles, in taxis, on transit) or walked or biked. These transit users have been termed *transit-dependent* or *captive* riders.

HUMAN FACTORS

Transit passengers frequently rely on other modes to gain access to transit. Typical transit users do not have transit service available at the door and must walk, bicycle, or drive to a transit stop and walk or bicycle from the transit discharge point to their destination. Consequently, transit use is greater where population and job densities are higher and access options are good.

Unlike other modes, transit is primarily focused on a service rather than a facility.

Unlike the other modes addressed in the HCM, transit is primarily focused on a service rather than a facility. Roadways, bicycle lanes, and sidewalks, once constructed, are generally available at all times to users. Transit service, in contrast, is only available at designated times and places. Another important difference is that all transit users are passengers, rather than drivers, and not in direct control of their travel. Thus, the frequency and reliability of service are important quality-of-service factors for transit users. Travel speed and comfort while making a trip are also important to transit users.

In evaluating priority measures for transit, the number of people affected is often more relevant than the number of vehicles affected.

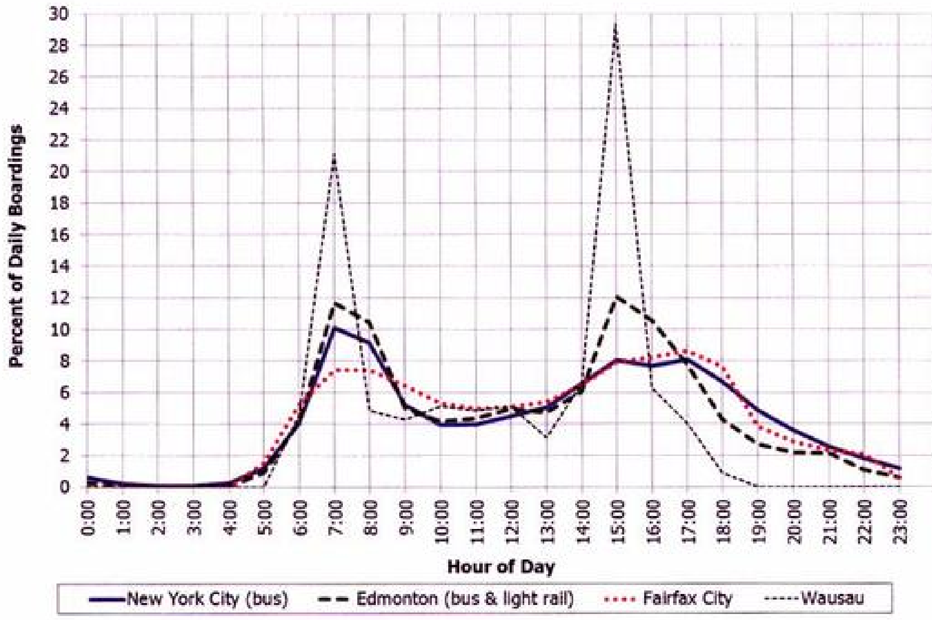
Transit is about moving people rather than vehicles. Transit operations at their most efficient level involve relatively few vehicles, each carrying a large number of passengers. In contrast, roadway capacity analysis typically involves relatively large numbers of vehicles, most carrying only a single occupant. In evaluating priority measures for transit, the number of people affected is often more relevant than the number of vehicles.

VARIATIONS IN DEMAND

Similar to other modes, transit passenger demand has distinct peaking patterns. Although these patterns typically coincide with peak commuting periods and—in many cases—school schedules, the patterns can vary substantially with the size and type of transit market being served. As an illustration, Exhibit 3-26 shows peaking patterns associated with four transit systems (*20*):

- Wausau, Wisconsin (2011 population 39,000), a relatively small community where school travel dominates transit demand patterns;
- Fairfax City, Virginia (population 25,000), a suburb of Washington, D.C., whose two-line bus system serves both commuter demands into the center of the region and student demands from the region to the university located in the city;
- Edmonton, Alberta, Canada (population 812,000), a sprawling city with bus and light rail service, a major university, and significant downtown employment; and
- New York City (population 8.2 million), a very dense city offering a variety of transportation options.

Exhibit 3-26
Illustrative Time-of-Day Variations in Transit Demand



Sources: Lu and Reddy (*27*), City of Edmonton (*28*), Connetics Transportation Group (*29*), Urbitran Associates and Abrams-Cherwony & Associates (*30*), presented in the *Transit Capacity and Quality of Service Manual* (*20*).

In all cases, an a.m. and a p.m. peak can be observed, but the sharpness of the peak differs from one location to the next. As regional population increases and the difference between peak-direction and off-peak-direction travel demand lessens, the relative size of the peak decreases. This characteristic has implications for the number of transit vehicles and drivers needed to provide service—fewer vehicles and drivers are needed solely to serve peak demand when smaller peaks exist—which, in turn, affects transit operating costs (*20*).

ON-STREET TRANSIT CHARACTERISTICS

The TCQSM comprehensively addresses transit modes.

The HCM addresses only those fixed-route transit modes that operate on roadways and interact with other roadway users. These modes are buses, streetcars, and light rail, illustrated in Exhibit 3-27 and described briefly in the following sections. The *Transit Capacity and Quality of Service Manual* (*20*) comprehensively describes transit mode characteristics.

Exhibit 3-27
Transit Modes Addressed in the HCM

(a) Bus (b) Streetcar (c) Light Rail

Bus

The bus mode is operated by rubber-tired vehicles that follow fixed routes and schedules along roadways. Although the electric trolleybus (a bus receiving its power from overhead electric wires) and bus rapid transit are classified as separate modes by the Federal Transit Administration, for HCM purposes they are treated as buses. The bus mode offers considerable operational flexibility. Service can range from local buses stopping every two to three blocks along a street, to limited-stop or bus rapid transit service stopping every ½ to 1 mi, to express service that travels along a roadway without stopping. Exhibit 3-28 provides typical acceleration characteristics of transit buses.

Exhibit 3-28
Transit Bus Acceleration Characteristics

	Average Time to Reach Speed (s)			Average Acceleration to Speed (ft/s²)	
Bus Type	**10 mi/h**	**20 mi/h**	**50 mi/h**	**20 mi/h**	**50 mi/h**
40-ft standard diesel	5.0	8.7	33.2	3.4	2.2
45-ft motor coach diesel	4.0	7.4	27.1	4.0	2.7
60-ft articulated diesel	4.0–4.7	9.1	42.3–43.6	3.2	1.7
Double deck diesel	6.2	10.4	43.6	2.8	1.7
60-ft articulated hybrid	3.8	8.6	35.2	3.4	2.1

Source: Hemily and King (*31*).

Streetcar and Light Rail

The streetcar and light rail modes are operated by vehicles that receive power from overhead electric wires and run on tracks. Streetcars tend to be shorter and narrower, to be more likely to operate in mixed traffic, and to have shorter stop spacings than light rail trains.

ON-STREET TRANSIT FACILITY TYPES

Mixed Traffic

More than 99% of the bus route miles in the United States are operated in mixed traffic. In contrast, most rail route miles—other than portions of streetcar lines—operate in some form of segregated right-of-way. In mixed traffic, transit vehicles are subject to the same causes of delay as are other motorized vehicles, and they need to stop periodically to serve passengers. These stops can cause transit vehicles to fall out of any traffic signal progression that might be provided along the street and to incur greater signal delay than other vehicles.

Exclusive Lanes

Exclusive lanes are on-street lanes dedicated for use by transit vehicles on either a full-time or a part-time basis. They are generally separated from other lanes by just a stripe, and buses may be able to leave the exclusive lane to pass buses or obstructions such as delivery trucks. Right-turning traffic, bicycles, carpools, and taxis are sometimes allowed in exclusive bus lanes. Generally, no other traffic, with the possible exception of transit buses, is allowed in exclusive lanes provided for rail transit vehicles. Exclusive lanes allow transit vehicles to bypass queues of vehicles in the general traffic lanes and reduce or eliminate delays to transit vehicles caused by right-turning traffic. Therefore, these lanes can provide faster, more reliable transit operations.

On-Street Transitways

Buses and trains sometimes operate within a portion of the street right-of-way that is physically segregated from other traffic: in the median or adjacent to one side of the street. No other traffic is allowed in the transitway. The amount of green time allocated to transit vehicles may be different from the amount of time allocated to the parallel through movements—for example, it might be reduced to provide time to serve conflicting vehicular turning movements.

EFFECTS OF OTHER MODES

Automobiles and Trucks

Higher motorized vehicle volumes result in greater delays for all traffic, including buses. In locations where buses pull out of the travel lane to serve bus stops and yield-to-bus laws are not in place (or generally observed), buses experience delay waiting for a gap to pull back into traffic after serving a stop. Day-to-day variations in roadway congestion and trip-to-trip variations in making or missing green phases at signalized intersections affect bus schedule reliability. No HCM techniques exist to predict this impact.

Pedestrians

Transit users are typically pedestrians immediately before and after their trip aboard a transit vehicle, so the quality of the pedestrian environment along access routes to transit stops affects the quality of the transit trip. Pedestrians can delay buses in the same way that they delay automobiles, as described earlier in this chapter.

Bicycles

In locations where buses pull out of the travel lane to serve bus stops, bicycles may delay buses waiting for a gap to pull back into traffic, similar to automobiles. Transit users may be bicyclists before or after their trip, so the quality of the bicycling environment along access routes to transit stops and the ability of bicyclists to bring their bicycles with them on a transit vehicle influence the quality of the transit trip.

7. REFERENCES

Many of these references can be found in the Technical Reference Library in Volume 4.

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CHAPTER 4
TRAFFIC OPERATIONS AND CAPACITY CONCEPTS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

OVERVIEW

The relationships between volume (flow rate), speed, and density are among the most fundamental in transportation engineering and can be used to describe traffic operations on any roadway. Similar principles apply to the pedestrian and transit modes, while bicycle speeds are primarily affected by facility grade and conditions, interactions with other modes, and bicyclist age and fitness level.

Capacity represents the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform segment of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions. Reasonable expectancy is the basis for defining capacity. A given system element's capacity is a flow rate that can be achieved repeatedly under the same prevailing conditions, as opposed to being the maximum flow rate that might ever be observed. Since the prevailing conditions (e.g., weather, mix of heavy vehicles) will vary within the day or from one day to the next, a system element's capacity at a given time will also vary.

CHAPTER ORGANIZATION

Chapter 4 describes how basic traffic operations relationships apply to the four travel modes covered by the *Highway Capacity Manual* (HCM).

Section 2 provides basic traffic operations relationships for the motorized vehicle mode, introduces the concept of travel time reliability, and describes additional parameters that can be used to describe aspects of traffic flow on interrupted- and uninterrupted-flow system elements. This section also provides capacity concepts for the motorized vehicle mode and describes three approaches for estimating traffic flow parameters.

Section 3 presents speed, flow, and density relationships for the pedestrian mode and capacity concepts for pedestrian circulation and queuing areas. Section 4 provides bicycle flow parameters and capacity concepts and describes the importance of stops and delay as measures of bicycle traffic operations. Finally, Section 5 describes the bus operations, bus vehicle, roadway infrastructure, traffic control, and passenger characteristics that influence bus speeds. The section also presents transit vehicle and person capacity concepts.

RELATED HCM CONTENT

Several of the operational performance measures presented in Chapter 4 (speed, delay, and density, in particular) are used in Chapter 5 to describe the quality of service provided by a roadway, or—in the case of the volume-to-capacity (demand-to-capacity) ratio—are used to define the threshold between Levels of Service (LOS) E and F.

Details of traffic operations and capacity relationships specific to a particular system element (for example, speed–flow curves for freeways) are provided in the "capacity concepts" subsections of the chapters in Volumes 2 and 3.

2. MOTORIZED VEHICLE MODE

A few basic parameters—volume, flow rate, speed, and density—can be used to describe traffic operations on any roadway. In the HCM, volume, flow rate, and speed are parameters common to both uninterrupted- and interrupted-flow facilities, but density applies primarily to uninterrupted flow. Some parameters related to flow rate, such as spacing and headway, are also used for both types of facilities. Other parameters, such as saturation flow and gap, are specific to interrupted flow.

BASIC MOTORIZED VEHICLE FLOW PARAMETERS

Volume and Flow Rate

Volume and flow rate are two measures that quantify the number of vehicles passing a point on a lane or roadway during a given time interval. These terms are defined as follows:

- *Volume*—the total number of vehicles passing over a given point or section of a lane or roadway during a given time interval; any time interval can be used, but volumes are typically expressed in terms of annual, daily, hourly, or subhourly periods.
- *Flow rate*—the equivalent hourly rate at which vehicles pass over a given point or section of a lane or roadway during a given time interval of less than 1 h, usually 15 min. This chapter focuses on flow rate and the variations in flow that can occur over the course of an hour.

Flow rate is the equivalent hourly volume that would occur if a subhourly flow was sustained for an entire hour.

There is a distinction between volume and flow rate. Volume is the number of vehicles observed or predicted to pass a point during a time interval. Flow rate represents the number of vehicles passing a point during a time interval less than 1 h, but expressed as an equivalent hourly rate. A flow rate is the number of vehicles observed in a subhourly period, divided by the time (in hours) of the observation. For example, a volume of 100 veh observed in a 15-min period implies a flow rate of 100 veh divided by 0.25 h, or 400 veh/h.

Observed volumes may reflect capacity constraints rather than true demand. Demand is usually the desired input to HCM analyses, although it is not always easy to determine.

Volume and flow rate are variables that help quantify *demand,* that is, the number of users (often expressed as the number of vehicles) who *desire* to use a given system element during a specific time period, typically 1 h or 15 min. Volume and flow rate also help quantify capacity, that is, the number of users who *can* use a given system element during a specific time period. As discussed in Chapter 3, Modal Characteristics, observed volumes may reflect upstream capacity constraints rather than the true demand that would exist without the presence of a bottleneck.

In many cases, demand volumes are the desired input to HCM analyses. (The analysis of traffic conditions downstream of a bottleneck that is not planned to be removed is an example of an exception.) When conditions are *undersaturated* (i.e., demand is less than capacity) and no upstream bottlenecks exist, demand volume at a location equivalent to the measured volume at that location can be assumed. Otherwise, ascertaining demand requires a count of undersaturated traffic upstream of a bottleneck (i.e., a count of arrival volume rather than departure volume) (1). When the queue from a bottleneck extends past the previous intersection or interchange, how much of the traffic approaching the end of the queue is actually destined for the bottleneck location may not be easy to determine. Furthermore, as illustrated in Chapter 3, demand patterns may change after a bottleneck is removed. Nevertheless, where bottlenecks exist, neglecting to use demand volumes as inputs to HCM methodologies will produce results that underestimate the presence and extent of congestion. In other words, using observed volumes instead of demand volumes will likely lead to inaccurate HCM results.

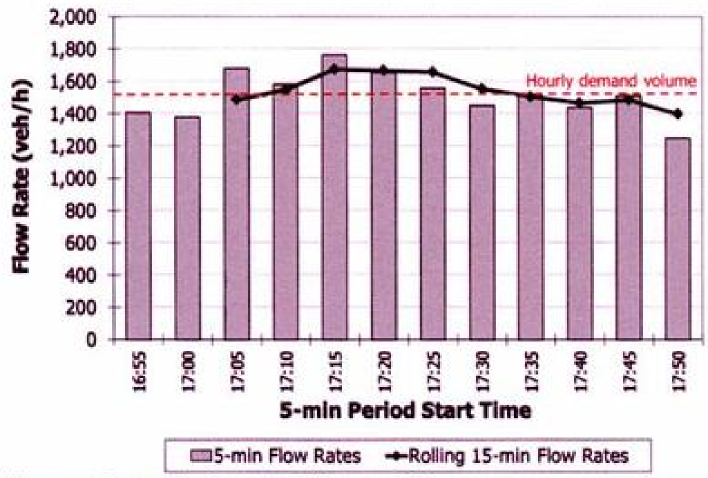
Using field-measured volumes as inputs to HCM methods without accounting for demand upstream of a bottleneck will lead to inaccurate results, such as demand-to-capacity ratios that can never exceed 1.

Subhourly Variations in Flow

Flow rates typically vary over the course of an hour. Exhibit 4-1 shows an example of the substantial short-term fluctuation in flow rate that can occur within an hour. Data from the approaches to an all-way STOP-controlled intersection are used. In this data set, the 5-min flow rate ranges from a low of 1,248 veh/h to a high of 1,764 veh/h, compared with a total peak hour entering volume of 1,516 veh. Designing the intersection to accommodate the peak hour volume would result in oversaturated conditions for a substantial portion of the hour.

Even when hourly volumes are less than a system element's capacity, flow rates within an hour may exceed capacity, creating oversaturated conditions.

Exhibit 4-1
Differences Between Short-Term Flow Rates and Hourly Demand Volumes



Note: SW 72nd Avenue at Dartmouth Street, Tigard, Oregon, 2008.

HCM analyses typically consider the peak 15 min of flow during the analysis hour. As illustrated in Exhibit 4-1, the use of a peak 15-min flow rate accommodates nearly all the variations in flow during the hour and therefore provides a good middle ground between designing for hourly volumes and designing for the most extreme 5-min flow rate.

Since inputs to HCM procedures are typically expressed in terms of hourly demands, the HCM uses the *peak hour factor* (PHF) to convert an hourly volume into a peak 15-min flow rate. Although traditionally called a "peak hour" factor, a PHF is applicable to any analysis hour, peak or off-peak. The PHF is the ratio of total hourly volume to the peak flow rate within the hour:

Peak hour factor (PHF) defined.

$$PHF = \frac{\text{hourly volume}}{\text{peak flow rate (within the hour)}}$$

Equation 4-1

If 15-min periods are used, the PHF may be computed by Equation 4-2:

Equation 4-2

$$PHF = \frac{V}{4 \times V_{15}}$$

where

PHF = peak hour factor,

V = hourly volume (veh/h), and

V_{15} = volume during the peak 15 min of the analysis hour (veh/15 min).

When the PHF is known, it can convert a peak hour volume to a peak flow rate, as in Equation 4-3:

Equation 4-3

$$v = \frac{V}{PHF}$$

where v is the flow rate for a peak 15-min period, expressed in vehicles per hour, and the other variables are as defined previously.

Equation 4-3 does not need to be used to estimate peak flow rates if traffic counts are available; however, the chosen count interval must identify the maximum 15-min flow period. Then the rate can be computed directly as 4 times the maximum 15-min count and the PHF would take the value 1.00.

Lower PHF values signify greater variability of flow, while higher values signify less flow variation within the hour. When hourly counts are used, the PHF can range from 1.00, indicating that the same demand occurs during each 15-min period of the hour, to a theoretical minimum of 0.25, indicating that the entire hourly demand occurs during the peak 15 min. PHFs in urban areas generally range between 0.80 and 0.98. PHFs over 0.95 are often indicative of high traffic volumes, sometimes with capacity constraints on flow during the peak hour. PHFs under 0.80 occur in locations with highly peaked demand, such as schools, factories with shift changes, and venues with scheduled events.

Speed

Although traffic volumes provide a method of quantifying capacity values, speed (or its reciprocal, *travel time rate*) is an important measure of the quality of the traffic service provided to the motorist. It helps define LOS for two-lane highways and urban streets.

Speed parameters.

Speed is defined as a rate of motion expressed as distance per unit of time, generally as miles per hour (mi/h). To characterize the speed of a traffic stream, a representative value must be used, because a broad distribution of individual speeds is observable in the traffic stream. Several speed parameters can be applied to a traffic stream. Among them are the following:

Average travel speed is a type of space mean speed.

- *Average travel speed*. The length of a roadway segment divided by the average travel time of vehicles traversing the segment, including all stopped delay times. It is a type of *space mean speed* because the average travel time weights the average by the time each vehicle spends in a defined roadway segment or space.

- *Time mean speed.* The arithmetic average of speeds of vehicles observed passing a point on a highway; also referred to as the *average spot speed*. The individual speeds of vehicles passing a point are recorded and averaged arithmetically. The time mean speed is always equal to or higher than the space mean speed. The two are equal only when the speeds of all vehicles in the traffic stream are equal.

A field-measured time mean speed will always be higher than the space mean speed, unless all vehicles in the traffic stream travel at the same speed, in which case the time mean speed will equal the space mean speed.

- *Free-flow speed.* The average speed of vehicles on a given segment, measured under low-volume conditions, when drivers are free to drive at their desired speed and are not constrained by the presence of other vehicles or downstream traffic control devices (i.e., traffic signals, roundabouts, or STOP signs).

Free-flow speed reflects drivers' desired speed, unconstrained by other vehicles or traffic control.

- *Average running speed.* A traffic stream measure based on the observation of travel times of vehicles traversing a section of highway of known length. It is the length of the segment divided by the average running time of vehicles that traverse the segment. Running time includes only time during which vehicles are in motion.

Average running speed only considers time spent in motion. It is also a type of space mean speed.

For most of the HCM procedures using speed as a service measure, average travel speed is the defining parameter. On uninterrupted-flow facilities operating with undersaturated flow, the average travel speed is equal to the average running speed.

Both time mean speed and space mean speed can be calculated from a sample of individual vehicle speeds. For example, three vehicles are recorded by a spot sensor (e.g., loop detectors, radar) with speeds of 30, 40, and 50 mi/h in the middle of a 1-mi roadway segment. The travel times for the same vehicles over the 1-mi segment are measured as 2.0 min, 1.5 min, and 1.2 min, respectively (i.e., by recording the times the vehicles enter and exit the segment). The time mean speed is 40 mi/h, calculated as (30 + 40 + 50 mi/h)/3. The space mean speed is 38.3 mi/h, calculated as (60 min/h) × [3/(2.0 + 1.5 + 1.2 min/mi)].

Space mean speed is recommended for HCM analyses. Speeds are best measured by observing travel times over a known length of highway. For uninterrupted-flow facilities operating in the range of stable flow, the length may be as short as several hundred feet for ease of observation.

Density

Density is the number of vehicles occupying a given length of a lane or roadway at a particular instant. For the computations in this manual, density is averaged over time and is usually expressed as vehicles per mile (veh/mi) or passenger cars per mile (pc/mi).

Computing density.

Measuring density directly in the field is difficult: it requires a vantage point for photographing, videotaping, or observing significant lengths of highway. However, density can be computed from the average travel speed and flow rate, which are measured more easily. Equation 4-4 is used for undersaturated traffic conditions.

$$\text{Density (veh/mi)} = \frac{\text{flow rate (veh/h)}}{\text{average travel speed (mi/h)}}$$

Equation 4-4

A highway segment with a flow rate of 1,000 veh/h and an average travel speed of 50 mi/h would have a density of (1,000 veh/h) / (50 mi/h) = 20 veh/mi.

Density is a critical parameter for uninterrupted-flow facilities because it characterizes the quality of traffic operations. It describes the proximity of vehicles to one another and reflects the freedom to maneuver within the traffic stream.

Roadway occupancy is frequently used as a surrogate for density in control systems because it is easier to measure (most often through equipment such as loop detectors). Occupancy in space is the proportion of roadway length covered by vehicles, and occupancy in time identifies the proportion of time a roadway cross section is occupied by vehicles. However, unless the length of vehicles is known precisely, the conversion from occupancy to density involves some error. A textbook (2) discusses derivation of occupancy and its relationship to density.

Headway and Spacing

Headway is the time between successive vehicles as they pass a point on a lane or roadway, measured from the same point on each vehicle. *Spacing* is the distance between successive vehicles in a traffic stream, measured from the same point on each vehicle (e.g., front bumper, front axle).

These characteristics are microscopic, because they relate to individual pairs of vehicles within the traffic stream. Within any traffic stream, both the spacing and the headway of individual vehicles are distributed over a range of values, generally related to the speed of the traffic stream and prevailing conditions. In the aggregate, these microscopic parameters relate to the macroscopic flow parameters of density and flow rate.

Relationships among density, speed and flow rate, and headway and spacing.

Spacing can be determined directly by measuring the distance between common points on successive vehicles at a particular instant. This generally requires costly aerial photographic techniques, so that spacing is usually derived from other direct measurements. Headway, in contrast, can be measured with stopwatch observations as vehicles pass a point on the roadway.

The density of a traffic stream is directly related to the average spacing between vehicles in the traffic stream:

Equation 4-5

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

The flow rate of a traffic stream is directly related to the average headway of vehicles in the traffic stream:

Equation 4-6

$$\text{Flow rate (veh/h)} = \frac{3{,}600\ \text{s/h}}{\text{average headway (s/veh)}}$$

Finally, the relationship between average spacing and average headway in a traffic stream depends on speed. This relationship can be derived from the preceding two equations and the speed–flow–density relationship (Equation 4-4):

Equation 4-7

$$\text{Average headway (s/veh)} = \frac{\text{average spacing (ft/veh)}}{\text{average travel speed (ft/s)}}$$

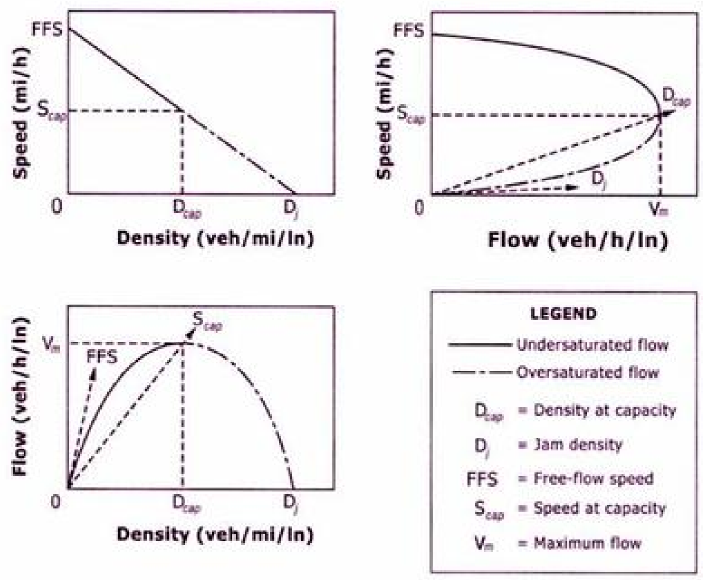
This relationship also holds for individual headways and spacings between pairs of vehicles. The speed used is that of the second vehicle in a pair.

Relationships Among Basic Parameters

Equation 4-4 cites the basic relationship among the three parameters, describing an uninterrupted traffic stream. Although Equation 4-4 allows for a given flow rate to occur in an infinite number of combinations of speed and density, additional relationships restrict the variety of flow conditions that can occur at a location.

Exhibit 4-2 shows a generalized, theoretical representation of these relationships, which are the basis for the capacity analysis of uninterrupted-flow facilities. The flow–density function is placed directly below the speed–density relationship because of their common horizontal scales, and the speed–flow function is placed next to the speed–density relationship because of their common vertical scales. The speed in all cases is *space mean speed*.

Exhibit 4-2
Generalized Relationships Among Speed, Density, and Flow Rate on Uninterrupted-Flow Facilities



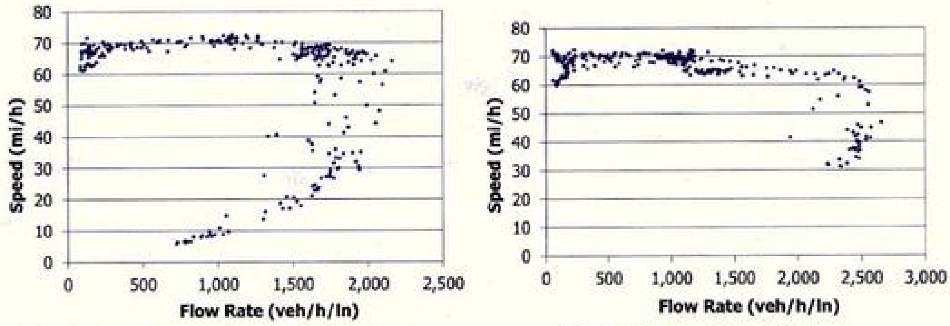
Source: Adapted from May (*2*).

Undersaturated, oversaturated, and queue discharge flow conditions were introduced in Section 5 of Chapter 2, Applications.

The form of these functions depends on the prevailing traffic and roadway conditions on the segment under study and on the segment length. Although the diagrams in Exhibit 4-2 show continuous curves, the full range of the functions is unlikely to appear at any particular location. Real-world data usually show discontinuities, with parts of the curves not present (2). Exhibit 4-3 shows that the real-world relationship between speed and undersaturated flow on freeways consists of a section of constant speed, followed by a section of declining speed until capacity is reached, unlike the idealized parabola shown in the speed–flow curve in Exhibit 4-2. Exhibit 4-3(a) shows a relatively complete curve, while Exhibit 4-3(b) has discontinuities. In addition, Exhibit 4-3 shows that a region of queue discharge flow exists between the two parts of the curves, where vehicles transition from oversaturated flow back to undersaturated flow after exiting a bottleneck.

Exhibit 4-3
Example Freeway Speed–Flow Data

Note that the real-world speed–flow curves in Exhibit 4-3 are not the idealized parabola indicated in Exhibit 4-2. The other relationships in Exhibit 4-2 therefore also have somewhat different shapes in the real world.



(a) I-405, Los Angeles, California

(b) I-805, San Diego, California

Source: Derived from California Department of Transportation data, 2008.

The curves of Exhibit 4-2 illustrate several significant details. A zero flow rate occurs under two different conditions. The first is when there are no vehicles on the segment—density is zero, and flow rate is zero. Speed is theoretical for this condition and would be selected by the first driver (presumably at a high value). This *free-flow speed* is represented by *FFS* in the graphs.

The second condition occurs when density becomes so high that all vehicles must stop—the speed and flow rate are zero because there is no movement and vehicles cannot pass a point on the roadway. The density at which all movement stops is called *jam density*, denoted by D_j in the diagrams.

Between these two extreme points, the dynamics of traffic flow produce a maximizing effect. As flow increases from zero, density also increases because more vehicles are on the roadway. When this happens, speed declines because of the interaction of vehicles. The decline is negligible at low and medium densities and flow rates and vehicles operate at the free-flow speed, as illustrated in Exhibit 4-3. As density increases, the generalized curves suggest that speed decreases significantly before capacity is achieved. Capacity is reached when the product of density and speed results in the maximum flow rate. This condition is shown as the speed at capacity S_{cap} (often called *critical speed*), density at capacity D_{cap} (sometimes referred to as *critical density*), and maximum flow v_m.

The slope of any ray drawn from the origin of the speed–flow curve represents the inverse of density, on the basis of Equation 4-4. Similarly, a ray in the flow–density graph represents speed. As examples, Exhibit 4-2 shows the average free-flow speed and speed at capacity, as well as optimum and jam densities. The three diagrams are redundant—if any one relationship is known, the other two are uniquely defined. The speed–density function is used mostly for theoretical work; the other two are used in this manual to define LOS for freeways and multilane highways.

Exhibit 4-2 shows that any flow rate other than capacity can occur under two conditions, one low density and high speed and the other high density and low speed. The high-density, low-speed side of the curves represents oversaturated flow. Sudden changes can occur in the state of traffic (i.e., in speed, density, and flow rate). LOS A through E are defined on the low-density, high-speed side of the curves, with the maximum-flow boundary of LOS E placed at capacity; in contrast, LOS F, which describes oversaturated and queue discharge traffic, is represented by the high-density, low-speed part of the curves.

TRAVEL TIME RELIABILITY

Sources of Travel Time Variability

The travel time experienced by a traveler on a given roadway facility varies from one trip to the next. The variation is a result of the following:

Travel time reliability is influenced by demand variations, weather, incidents, work zones, and special events, all of which can be modeled by HCM methods.

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

Reliability analysis accounts for nonrecurring traffic conditions and events that normally cannot be accounted for by the core HCM methods.

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

Defining and Expressing Reliability

Travel time reliability quantifies the variation of travel time. It is defined by using the entire range of travel times for a given trip for a selected time period (for example, the weekday p.m. peak hour) and over a selected horizon (for example, a year). For the purpose of measuring reliability, a "trip" can occur on a specific facility or on a subset of the transportation network, or the definition can be broadened to include a traveler's initial origin and final destination. Measurement of travel time reliability requires a history of travel times sufficient to track travel time performance. When travel time measurements are taken over a long period (e.g., a year), a travel time distribution results (*3*).

A travel time distribution may be characterized in one of two ways. Both methods have useful applications and are valuable for understanding and describing reliability. They are as follows:

1. Measures of the *variability* in travel times that occur on a facility or a trip over the course of time, as expressed through metrics such as a 50th, 80th, or 95th percentile travel time; and

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

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

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

For convenience, the HCM uses the single term *reliability* for both the variability- and the reliability-based approaches to characterizing a facility's travel time distribution.

Similar approaches can be used to describe the variability in other HCM facility performance measures, including percentiles (e.g., 50th percentile speed) and the probability of achieving a particular LOS. For freeway facilities, distributions can be produced for such measures as facility speed, travel time, and average density. For urban streets, distributions can be produced for travel time, travel speed, and spatial stop rate, among others.

Performance Measures Derived from the Travel Time Distribution

Time-Based Reliability Measures

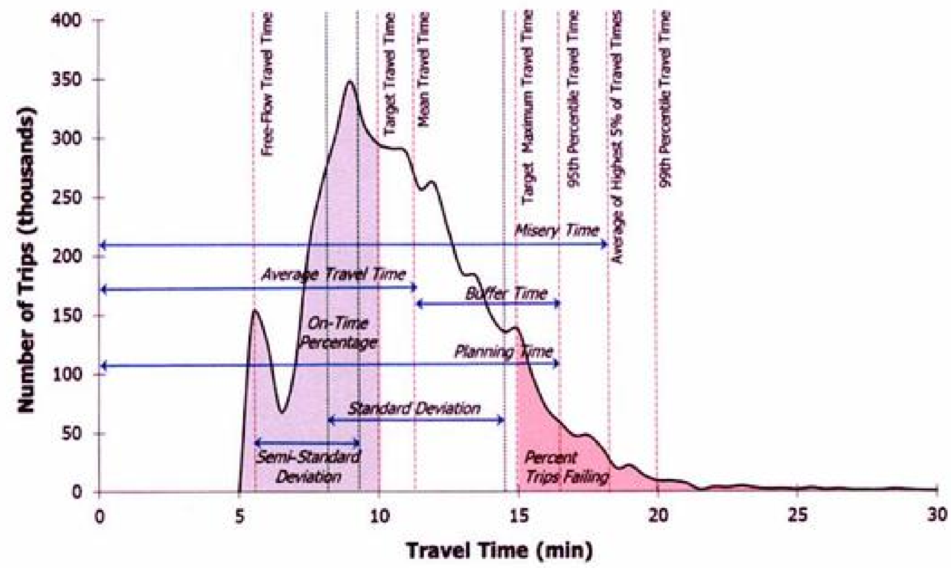
The travel time distribution can be used to derive a variety of performance measures that describe different aspects of reliability. Exhibit 4-4 illustrates a selection of time-based reliability performance measures that can be derived from the travel time distribution:

Planning time is the total *travel time required for an on-time arrival 95% of the time, while buffer time is the* extra *travel time beyond the average travel time required for an on-time arrival 95% of the time.*

- *Planning time,* the travel time a traveler would need to budget to ensure an on-time arrival 95% of the time;
- *Buffer time,* the extra travel time a traveler would need to budget, compared with the average travel time, to ensure an on-time arrival 95% of the time;
- *Misery time,* the average of the highest 5% of travel times (approximating a 97.5 percentile travel time), representing a near-worst-case condition;
- *On-time percentage,* a measure of success based on the percentage of trips that are made within a target travel time;
- *Percentage of trips exceeding a target maximum travel time,* a measure of failure;
- *Standard deviation,* the statistical measure of how much travel times vary from the average; and
- *Semi–standard deviation,* a statistical measure of travel time variance from the free-flow speed.

Time-based measures are useful for describing the reliability of individual facilities and trips but are difficult to use for comparisons.

In Exhibit 4-4, measures incorporating units of time appear as horizontal lines in the graph, while measures that are percentages of trips appear as areas underneath the travel time distribution. The former are useful for describing the reliability of individual facilities and trips, but they are difficult to compare across facilities or trips because facility and trip lengths vary. Percentage measures, on the other hand, can be compared across facilities and trips, as can index-based measures that are derived from time-based measures. These types of reliability measures are described next.



Source: Adapted from Zegeer et al. (*3*).

Exhibit 4-4
Derivation of Time-Based Reliability Performance Measures from the Travel Time Distribution

Index-Based Reliability Measures

To facilitate comparisons of different facilities or trips, travel time–based reliability measures can be converted into length-independent indices by dividing the base travel time measure by the free-flow travel time. Similarly, success and failure measures can be developed by comparing an index value with a target value. The following are examples:

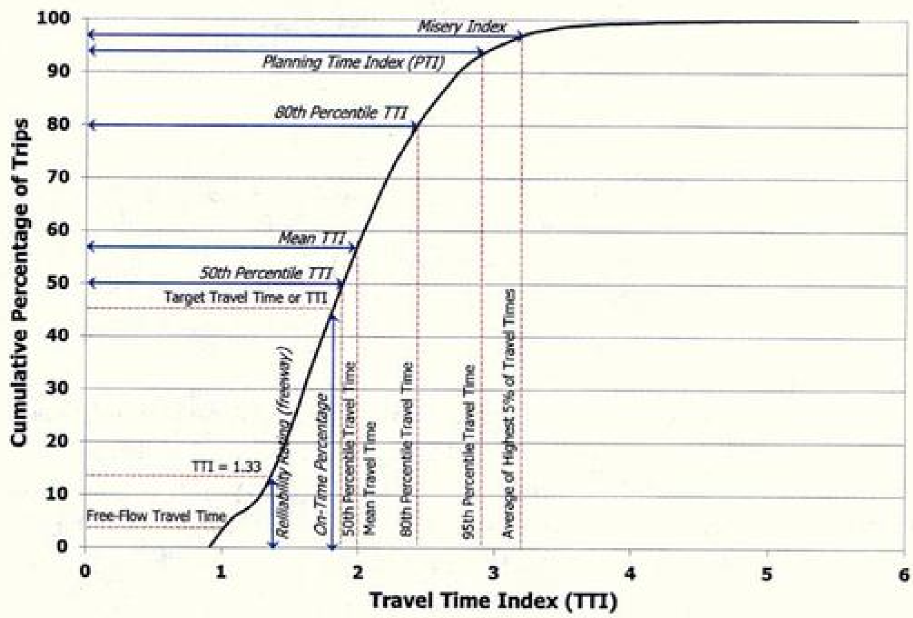
Index-based measures of reliability are independent of facility or trip length and thus are readily compared across facilities or trips.

- *Travel time index (TTI),* the average travel time on a facility divided by the travel time at free-flow speed; it can also be stated as a percentile travel time, as discussed below;
- *Planning time index (PTI),* the 95th percentile travel time divided by the free-flow travel time;
- *80th percentile TTI,* the 80th percentile travel time divided by the free-flow travel time; research indicates that this measure is more sensitive to operational changes than the PTI (*4*), which makes it useful for comparison and prioritization purposes;
- *50th percentile TTI,* the 50th percentile travel time divided by the free-flow travel time; its value will generally be slightly lower than the mean TTI due to the influence of rare, very long travel times in the travel time distribution;
- *Misery index,* the misery time divided by the free-flow travel time, a useful descriptor of near-worst-case conditions on rural facilities; and
- *Reliability rating,* the percentage of vehicle miles traveled experiencing a TTI less than 1.33 for freeways and 2.50 for urban streets; these thresholds approximate the points beyond which travel times become much more variable (unreliable).

The difference in threshold values for freeways and urban streets reflects differences in how free-flow speed is defined for these facilities.

Exhibit 4-5 illustrates a selection of index-based reliability measures. The same travel time distribution is used as in Exhibit 4-4, but travel times are converted to TTIs and the travel time distribution is plotted as a cumulative function. The mean travel time in this distribution happened to be exactly twice the free-flow travel time (i.e., a mean TTI of 2.00), but this result is coincidental. In this graph, index measure values are horizontal lines, while percentage measure values (e.g., on-time percentage, reliability rating) are vertical lines.

Exhibit 4-5
Derivation of Index-Based Reliability Performance Measures from the Travel Time Distribution



Other types of indices can be created by using a denominator other than free-flow travel time. For example, a *policy index* can be defined that is similar to the TTI but replaces free-flow speed with a target or "policy" speed, such as a desired minimum operating speed for the facility (typically chosen as a speed just above breakdown, thus providing maximum throughput).

The *buffer index* is the 95th percentile travel time divided by the average travel time. However, it is not recommended for tracking reliability trends over time because it is linked to two factors that can change: average and 95th percentile travel times. If one factor changes more in relation to the other, counterintuitive results can appear (*3, 4*).

ADDITIONAL UNINTERRUPTED-FLOW PARAMETERS

Headway

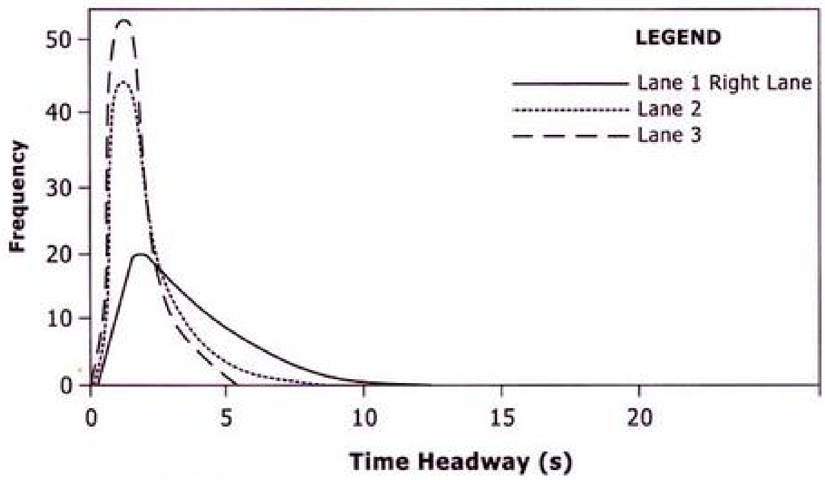
The average headway in a lane is the reciprocal of the flow rate. Thus, at a flow of 2,400 veh/h/ln, the average headway is (3,600 s/h) / (2,400 veh/h), or 1.5 s/veh. However, vehicles do not travel at constant headways. Vehicles tend to travel in groups (*platoons*), with varying headways between successive vehicles.

An example of the distribution of headways observed on the Long Island Expressway is shown in Exhibit 4-6. The headway distribution of Lane 3 is the most nearly uniform, as evidenced by the range of values and the high frequency of the modal value, which is the peak of the distribution curve. The distribution of Lane 2 is similar to that of Lane 3, with slightly greater scatter (range from 0.5 to 9.0 s). Lane 1 shows a much different pattern: it is more dispersed, with headways ranging from 0.5 to 12.0 s, and the frequency of the modal value is only about one-third of that for the other lanes. This indicates that the flow rate in the shoulder lane is usually lower than the flow rates in the adjacent lanes when the total flows on this segment are moderate to high.

Headway *includes the vehicle length, while* gap *is the space between vehicles.*

Exhibit 4-6 shows relatively few headways smaller than 1.0 s. A vehicle traveling at 60 mi/h (88 ft/s) would have a spacing of 88 ft with a 1.0-s headway and only 44 ft with a 0.5-s headway. This effectively reduces the space between vehicles (rear bumper to front bumper) to only 25 to 30 ft. This spacing (also called *gap*) would be extremely difficult to maintain.

Exhibit 4-6
Time Headway Distribution for Long Island Expressway



Source: Berry and Gandhi (*5*).

Drivers react to this intervehicle spacing, which they perceive directly, rather than to headway. Headway includes the length of the vehicle, which became smaller for passenger cars in the vehicle mix of the 1980s. In the 1990s and 2000s, because of the popularity of sport-utility vehicles, typical vehicle lengths increased. If drivers maintain the same intervehicle spacing and car lengths continue to increase, conceivably, decreases in capacity could result.

If traffic flow were truly random, small headways (less than 1.0 s) could theoretically occur. Several mathematical models have been developed that recognize the absence of small headways in most traffic streams (*6*).

Delay

Delay is the additional travel time experienced by a driver beyond that required to travel at a desired speed. The starting point for measuring delay for HCM purposes is the travel time at free-flow speed. However, it is also possible for reporting purposes to establish a maximum desired travel time, minimum travel speed, or minimum LOS from a transportation agency's point of view (e.g., a travel time for a segment or facility based on the speed at capacity) and to report a *threshold delay* as any additional travel time beyond the established threshold value.

There are several potential sources of delay on uninterrupted-flow facilities:

- *Traffic demand,* increasing levels of which cause drivers to reduce their speed from the free-flow speed because of increased vehicle interactions, as was illustrated in Exhibit 4-2 and Exhibit 4-3;
- *Incidents,* which can reduce the roadway capacity available to serve demand or simply cause drivers to slow down to observe what is happening (e.g., "rubbernecking");
- *Environmental conditions,* such as snow, heavy rain, or sun glare, that cause drivers to reduce their speed from the free-flow speed; and
- *Isolated control features,* such as manual toll collection, inspection stations, railroad grade crossings, or drawbridges on otherwise uninterrupted-flow facilities.

ADDITIONAL INTERRUPTED-FLOW PARAMETERS

Basic concepts for interrupted-flow facilities: intersection control, saturation flow rate, lost time, and queuing.

Interrupted flow can be more complex to analyze than uninterrupted flow because of the time dimension involved in allocating space to conflicting traffic streams. On an interrupted-flow facility, flow usually is dominated by points of fixed operation, such as traffic signals and STOP signs. These controls have different impacts on overall flow.

The operational state of traffic on an interrupted-flow facility is defined by the following measures:

- Volume and flow rate (discussed earlier in the chapter); and
- Control variables (signal, STOP, or YIELD control), which in turn influence
  - Saturation flow and departure headways,
  - Gaps available in the conflicting traffic streams, and
  - Control delay.

Signalized Intersection Flow

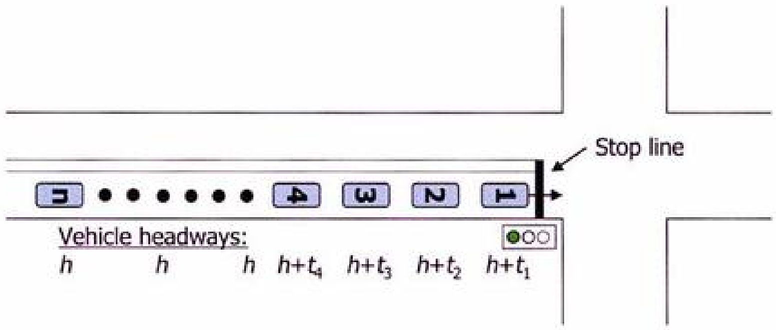
Saturation Flow

Impact of traffic signal control on maximum flow rate.

The most significant source of fixed interruptions on an interrupted-flow facility is traffic signals. A traffic signal periodically halts flow for each movement or set of movements. Movement on a given set of lanes is possible only for a portion of the total time, because the signal prohibits movement during some periods. Only the time during which the signal is effectively green is available for movement. For example, if one set of lanes at a signalized intersection receives a 30-s effective green time out of a 90-s total cycle, only 30/90 or one-third of total time is available for movement on the subject lanes. Thus, flow on the lanes can occur only for 20 min of each hour. If the lanes can accommodate a maximum flow rate of 1,500 veh/h with the signal green for a full hour, they can actually accommodate a total rate of flow of only 500 veh/h, since only one-third of each hour is available as green.

When the signal turns green, the dynamics of starting a stopped queue of vehicles must be considered. Exhibit 4-7 shows a queue of vehicles stopped at a signal. When the signal turns green, the queue begins to move. The headway between vehicles can be observed as the vehicles cross the stop line of the intersection. The first headway will be the elapsed time, in seconds, between the initiation of the green and the front wheels of the first vehicle crossing over the stop line. The second headway will be the elapsed time between the front bumpers (or wheels) of the first and second vehicles crossing over the stop line. Subsequent headways are measured similarly.

Exhibit 4-7
Acceleration Headways at a Signalized Intersection



The driver of the first vehicle in the queue must observe the signal change to green and react to the change by releasing the brake and accelerating through the intersection. As a result, the first headway will be comparatively long. The second vehicle in the queue follows a similar process, except that the reaction and acceleration period can occur while the first vehicle is beginning to move. The second vehicle will be moving faster than the first as it crosses the stop line, because it has a greater distance over which to accelerate. Its headway will generally be less than that of the first vehicle. The third and fourth vehicles follow a similar procedure, each achieving a slightly lower headway than the preceding vehicle. After four vehicles, the effect of the start-up reaction and acceleration has typically dissipated. Successive vehicles then move past the stop line at a more constant headway until the last vehicle in the original queue has passed the stop line.

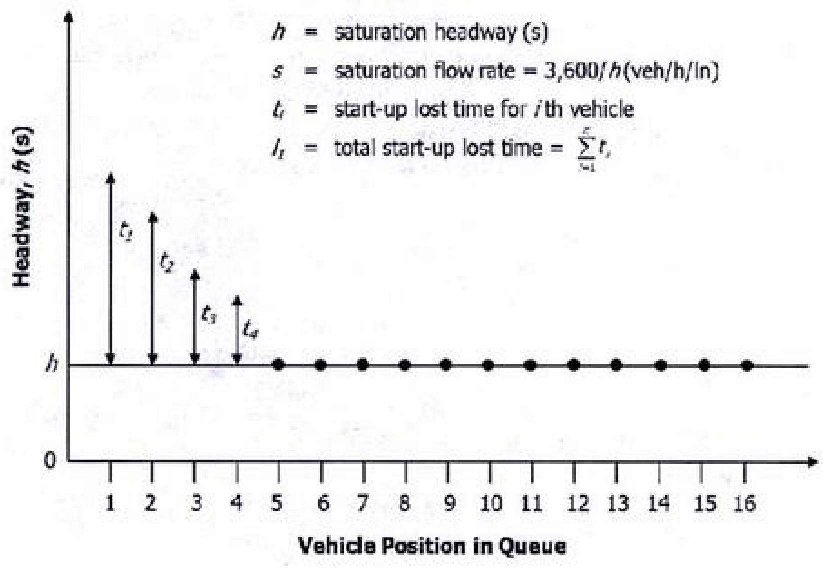
In Exhibit 4-7, this constant average headway, denoted as h, is achieved after four vehicles. The acceleration headways for the first four vehicles are, on the average, greater than h and are expressed as $h + t_i$, where t_i is the incremental headway for the ith vehicle due to the start-up reaction and acceleration. As i increases from 1 to 4, t_i decreases.

Exhibit 4-8 shows a conceptual plot of headways. The HCM recommends using the fifth vehicle following the beginning of a green as the starting point for saturation flow measurements.

The value h represents the *saturation headway*, estimated as the constant average headway between vehicles after the fourth vehicle in the queue and continuing until the last vehicle that was in the queue at the beginning of the green has cleared the intersection.

The reference point on the vehicle used to measure headways is typically the front bumper. Front axles are sometimes the reference point in studies utilizing tube counters to obtain the data.

Exhibit 4-8
Concept of Saturation Flow Rate and Lost Time



Saturation flow rate.

Saturation flow rate is defined as the flow rate per lane at which vehicles can pass through a signalized intersection. It is computed by Equation 4-8:

Equation 4-8

$$s = \frac{3{,}600}{h}$$

where s is the saturation flow rate (veh/h/ln) and h is the saturation headway (s).

The saturation flow rate is the number of vehicles per hour per lane that could pass through a signalized intersection if a green signal was displayed for the full hour, the flow of vehicles never stopped, and there were no large headways.

Lost Time

Each time a flow is stopped, it must start again, with the first four vehicles experiencing the start-up reaction and acceleration headways shown in Exhibit 4-7. In this exhibit, the first four vehicles in the queue encounter headways longer than the saturation headway, h. The increments, t_i, are called start-up lost times. The *total start-up lost time* for the vehicles is the sum of the increments, as computed by using Equation 4-9.

Total start-up lost time.

Equation 4-9

$$l_1 = \sum_{i=1}^{n} t_i$$

where

l_1 = total start-up lost time (s),

t_i = lost time for ith vehicle in queue (s), and

n = last vehicle in queue.

Each stop of a stream of vehicles is another source of lost time. When one stream of vehicles stops, safety requires some clearance time before a conflicting stream of traffic is allowed to enter the intersection. The interval when no vehicles use the intersection is called *clearance lost time,* l_2. In practice, signal cycles provide for this clearance through change intervals, which can include

Clearance lost time.

yellow or red-clearance indications, or both. Drivers use the intersection during some portion of these intervals.

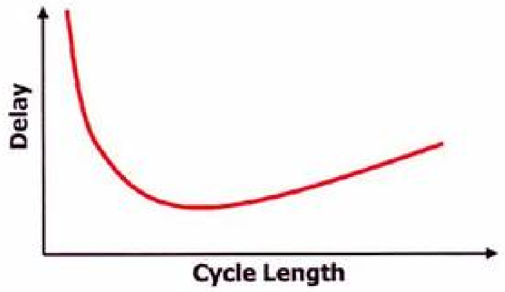
The relationship between saturation flow rate and lost times is critical. For any given lane or movement, vehicles use the intersection at the saturation flow rate for a period equal to the available green time plus the change interval minus the start-up and clearance lost times. Because lost time is experienced with each start and stop of a movement, the total amount of time lost over an hour is related to the signal timing. For example, if a signal has a 60-s cycle length, it will start and stop each movement 60 times per hour, and the total lost time per movement will be $60(l_1 + l_2)$.

Cycle Lengths

Lost time affects capacity and delay. As indicated by the relationship of cycle length to lost time, the capacity of an intersection increases as cycle length increases. However, the capacity increase can be offset somewhat by the observation that the saturation headway, *h*, can be longer when green times are long (e.g., greater than 50 s) (*7*). Capacity increases due to longer cycles are also often offset by the increase in delay that typically results from longer cycles, as discussed below. Other intersection features, such as turning lanes, can also offset the reduced capacity that results from short cycles. Longer cycles increase the number of vehicles in the queues and can cause the left-turn lane to overflow, reducing capacity by blocking the through lanes.

As indicated in Exhibit 4-9, there is a strong relationship between delay and cycle length. For every intersection there is a small range of cycle lengths that will result in the lowest average delay for motorists. Delay, however, is a complex variable affected by many variables besides cycle length.

Exhibit 4-9
Generalized Cycle Length and Delay Relationship



STOP- and YIELD-Controlled Intersection Flow

Two-Way STOP-Controlled Intersections

The driver on the minor street or the driver turning left from the major street at a two-way STOP-controlled intersection faces a specific task: selecting a gap in traffic through which to execute the desired movement. The term *gap* refers to the time interval (*time gap*) and corresponding distance for a given speed (*space gap*) between the major-street vehicles entering an unsignalized intersection, measured from back bumper to front bumper. The term *gap acceptance* describes the completion of a vehicle's movement into a gap.

The capacity of a minor-street approach depends on two factors:

- The distribution of available gaps in the major-street traffic stream, and
- The gap sizes required by drivers in other traffic streams to execute their desired movements.

Gap acceptance.

The distribution of available gaps in the major-street traffic stream depends on the total volume on the street, its directional distribution, the number of lanes on the major street, and the degree and type of platooning in the traffic stream. The gap sizes required by minor-movement drivers depend on the type of maneuver (left, through, right), the number of lanes on the major street, the speed of major-street traffic, sight distances, the length of time the minor-movement vehicle has been waiting, and driver characteristics (eyesight, reaction time, age, etc.).

Critical headway.

For ease of data collection, headways (e.g., front bumper to front bumper) are usually measured instead of gaps, since only half as much data are required (i.e., only front bumper positions need to be recorded, rather than both front and back bumper positions). The *critical headway* is the minimum time interval between the front bumpers of two successive vehicles in the major traffic stream that will allow the entry of one minor-street vehicle. When more than one minor-street vehicle uses one major-street gap, the time headway between the two minor-street vehicles is called *follow-up headway*. In general, the follow-up headway is shorter than the critical headway.

Roundabouts

The operation of roundabouts is similar to that of two-way STOP-controlled intersections. In roundabouts, however, entering drivers scan only one stream of traffic—the circulating stream—for an acceptable gap.

All-Way STOP-Controlled Intersections

At an all-way STOP-controlled intersection, all drivers must come to a complete stop. The decision to proceed is based in part on the rules of the road, which suggest that the driver on the right has the right-of-way, but it is also a function of the traffic condition on the other approaches. The departure headway for the subject approach is defined as the time between the departure of one vehicle and that of the next behind it. A departure headway is considered a saturation headway if the second vehicle stops behind the first at the stop line. If there is traffic on one approach only, vehicles can depart as rapidly as the drivers can safely accelerate into and clear the intersection. If traffic is present on other approaches, the saturation headway on the subject approach will increase, depending on the degree of conflict between vehicles.

Delay

As previously discussed in the section on uninterrupted-flow parameters, delay is the additional travel time experienced by a driver beyond that required to travel at a desired speed, and the starting point for measuring delay for HCM purposes is the travel time at free-flow speed.

Several types of delay are defined for interrupted-flow system elements, but *control delay*—the delay brought about by the presence of a traffic control device—is the principal HCM service measure for evaluating LOS at signalized and unsignalized intersections. Control delay includes delay when vehicles slow in advance of an intersection, time spent stopped on an intersection approach, time spent as vehicles move up in the queue, and time needed for vehicles to accelerate to their desired speed.

The following are other types of delay experienced on interrupted-flow roadways:

- *Traffic delay,* extra travel time resulting from the interaction of vehicles, causing drivers to reduce their speed below the free-flow speed;
- *Geometric delay,* extra travel time created by geometric features that cause drivers to reduce their speed (e.g., delay experienced where an arterial street makes a sharp turn, causing vehicles to slow, or the delay caused by the indirect route that through vehicles must take through a roundabout);
- *Incident delay,* the additional travel time experienced as a result of an incident, compared with the no-incident condition; and
- *Delay due to environmental conditions,* the additional travel time experienced due to severe weather conditions.

Transportation agencies may also choose to report a *threshold delay,* defined as the excess travel time that occurs beyond a defined speed or LOS established by norm (e.g., control delay exceeding LOS B, traffic operating at speeds less than 35 mi/h).

Number of Stops

Traffic control devices separate vehicles on conflicting paths by requiring one vehicle to stop or yield to the other. The stop causes delay and has an associated cost in terms of fuel consumption and wear on the vehicle. For this reason, information about stops incurred is useful in evaluating performance and calculating road user costs. This measure is typically expressed in terms of *stop rate,* which represents the count of stops divided by the number of vehicles served. Stop rate has units of stops per vehicle.

Stops are generally expected by motorists arriving at an intersection as a minor movement (e.g., a turn movement or a through movement on the minor street). However, through drivers do not expect to stop when they travel along a major street. Their expectation is that the signals will be coordinated to some degree such that they can arrive at each signal in succession while it is displaying a green indication for the through movement. For this reason, stop rate is a useful performance measure for evaluating coordinated signal systems.

Queuing

When demand exceeds capacity for a period of time or when an arrival headway is less than the service time (at the microscopic level) at a specific location, a queue forms (2). Queuing is both an important operational measure and a design consideration for an intersection and its vicinity. Queues that are longer than the available storage length can create several types of operational problems. A through-lane queue that extends past the entrance to a turn lane blocks access to the turn lane and keeps it from being used effectively. Similarly, a turn-lane queue overflow into a through lane interferes with the movement of through vehicles. Queues that extend upstream from an intersection can block access into and out of driveways and—in a worst case—can spill back into and block upstream intersections, causing side streets to begin to queue back.

Several queuing measures can be calculated, including the average queue length, the maximum back of queue, and the maximum probable queue (e.g., a 95th percentile queue).

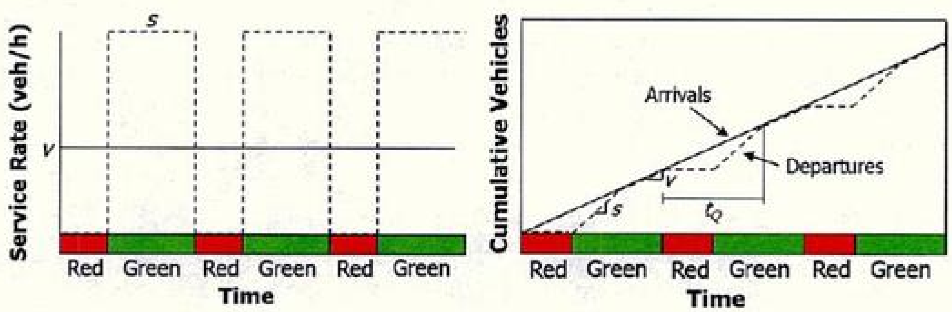
To predict the characteristics of a queuing system mathematically, the following system characteristics and parameters must be specified (*5*):

- Arrival pattern characteristics, including the average rate of arrival and the statistical distribution of time between arrivals;
- Service facility characteristics, including service-time average rates and the distribution and number of customers that can be served simultaneously or the number of channels available; and
- Queue discipline characteristics, such as the means of selecting which customer is next.

The arrival rate exceeds the service rate in oversaturated queues, while the arrival rate is less than the service rate in undersaturated queues. The length of an undersaturated queue can vary but will reach a steady state as more vehicles arrive. In contrast, the length of an oversaturated queue never reaches a steady state; it increases as more vehicles arrive until the arrival demand decreases.

An idealized undersaturated queue at a signalized intersection is shown in Exhibit 4-10. The exhibit assumes queuing on one approach at an intersection with two signal phases. In each cycle, the arrival demand (assumed to be constant in this ideal example) is less than the capacity of the approach, no vehicles wait longer than one cycle, and there is no overflow from one cycle to the next. Exhibit 4-10(a) specifies the arrival rate, *v*, in vehicles per hour; it is constant for the study period. The service rate, *s*, has two states: zero when the signal is effectively red and up to the saturation flow rate when the signal is effectively green. Note that the service rate is equal to the saturation flow rate only when there is a queue.

Exhibit 4-10
Idealized Queuing Diagram for a Two-Phase Signalized Intersection



(a) Arrival and Service Rates

(b) Queue Lengths

Source: May (*2*).

Exhibit 4-10(b) diagrams cumulative vehicles over time. The horizontal line, v, in Exhibit 4-10(a) becomes the solid line in Exhibit 4-10(b), with the slope of the line equal to the arrival rate. Transferring the service rate from Exhibit 4-10(a) to Exhibit 4-10(b) creates a different graph. During the red period, the service rate is zero, so the service rate is shown as a horizontal dashed line in Exhibit 4-10(b). At the start of the green period, a queue is present, and the service rate is equal to the saturation flow rate. This forms a series of triangles, with the cumulative arrival line as the top side of each triangle and the cumulative service line forming the other two sides, illustrating that a steady state has been reached.

Each triangle represents the queue buildup and dissipation during one cycle length and can be analyzed to calculate the duration of the queue. It starts at the beginning of the red period and continues until the queue dissipates. Its value varies between the effective red time and the cycle length, and it is computed by using Equation 4-10:

$$vt_Q = s(t_Q - r) \text{ or } t_Q = \frac{sr}{s - v}$$

Equation 4-10

where

t_Q = time duration of queue (s),

v = mean arrival rate (veh/h),

s = mean service rate (veh/h), and

r = effective red time (s).

The queue length (i.e., the number of vehicles in the queue, as opposed to the location of the back of the queue) is represented by the vertical distance through the triangle. At the beginning of red, the queue length is zero. It increases to its maximum value at the end of the red period. Then the queue length decreases until the arrival line intersects the service line and the queue length equals zero.

The queuing characteristics can be modeled by varying the arrival rate, the service rate, and the timing plan. In real-life situations, arrival rates and service rates are continuously changing. These variations complicate the model, but the basic relationships do not change.

CAPACITY CONCEPTS

Definition of Capacity

The *capacity* of a system element is the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions.

Vehicle capacity is the maximum number of vehicles that can pass a given point during a specified period under prevailing roadway, traffic, and control conditions. This assumes that there is no influence from downstream traffic operation, such as queues backing into the analysis point.

Person capacity is the maximum number of persons that can pass a given point during a specified period under prevailing conditions. Person capacity is commonly used to evaluate public transit services, high-occupancy-vehicle lanes, and pedestrian facilities.

Prevailing roadway, environmental, traffic, and control conditions define capacity; these conditions should be reasonably uniform for any segment of a facility that is analyzed. Any change in the prevailing conditions changes a system element's capacity. Thus, an element's capacity can vary from one hour to the next or from one day to the next, as the prevailing conditions (e.g., weather, heavy vehicle percentage, presence or absence of a queue) vary.

Capacity is defined on the basis of reasonable expectancy.

Reasonable expectancy is the basis for defining capacity. That is, the stated capacity for a given system element is a flow rate that can be achieved repeatedly for peak periods of sufficient demand. Stated capacity values can be achieved on system elements with similar characteristics throughout North America. Capacity is not the absolute maximum flow rate observed on such a system element. The absolute maximum flow rate can vary from day to day and from location to location.

Persons per hour, passenger cars per hour, and vehicles per hour are measures that can define capacity, depending on the type of system element and the type of analysis. The concept of person flow is important in making strategic decisions about transportation modes in heavily traveled corridors and in defining the role of transit and high-occupancy-vehicle priority treatments. Person capacity and person flow weight each type of vehicle in the traffic stream by the number of occupants carried.

Base Conditions

Base conditions defined.

Many of the procedures in this manual provide a formula or simple tabular or graphic presentations for a set of specified standard conditions, which must be adjusted to account for prevailing conditions that do not match. These standard conditions are termed *base conditions.*

Base conditions assume good weather, good and dry pavement conditions, users who are familiar with the system element, and no impediments to traffic flow. Other more specific base conditions are identified in each methodological chapter in Volumes 2 and 3.

Prevailing conditions almost always differ from the base conditions.

In most capacity analyses, prevailing conditions differ from the base conditions (e.g., there are trucks in the traffic stream, lanes are narrow). As a result, computations of capacity, service flow rate, and LOS must include adjustments. Prevailing conditions are generally categorized as roadway, traffic, control, operations, or environment.

Roadway Conditions

Impact of roadway conditions.

Roadway conditions include geometric and other elements. In some cases, they influence the capacity of a system element; in others, they can affect a performance measure such as speed, but not the roadway's capacity or maximum flow rate.

Roadway factors include the following:

- Number of lanes,
- The type of system element and its land use environment,
- Lane widths,
- Shoulder widths and lateral clearances,
- Design speed,
- Horizontal and vertical alignments, and
- Availability of exclusive turn lanes at intersections.

The horizontal and vertical alignments of a highway depend on the design speed and the topography of the land on which it is constructed.

In general, as the severity of the terrain increases, capacity and service flow rates are reduced. This is significant for two-lane rural highways, where the severity of terrain can affect the operating capabilities of individual vehicles in the traffic stream and restrict opportunities for passing slow-moving vehicles.

Traffic Conditions

Traffic conditions that influence capacities and service levels include vehicle type, lane or directional distribution, and the driver population.

Vehicle Type

The entry of heavy vehicles—that is, vehicles other than passenger cars (a category that includes small trucks and vans)—into the traffic stream affects the number of vehicles that can be served. Heavy vehicles are vehicles that have more than four tires touching the pavement.

Trucks, buses, and recreational vehicles are the three groups of heavy vehicles addressed by the methods in this manual. As discussed in Chapter 3, Modal Characteristics, heavy vehicles adversely affect traffic in two ways:

- They are larger than passenger cars, so they occupy more roadway space and create larger time headways between vehicles.
- They have poorer operating capabilities than passenger cars, particularly with respect to acceleration, deceleration, and the ability to maintain speed on upgrades.

At signalized intersections, the larger headways produced by trucks decrease the saturation flow rate.

The second impact is more critical. The inability of heavy vehicles to keep pace with passenger cars in many situations creates large gaps in the traffic stream, which are difficult to fill by passing maneuvers. Queues may also develop behind a slow-moving heavy vehicle. The resulting inefficiencies in the use of roadway space cannot be completely overcome. This effect is particularly harmful on sustained, steep upgrades, where the difference in operating capabilities is most pronounced, and on two-lane highways, where passing requires use of the opposing travel lane.

Heavy vehicles also can affect downgrade operations, particularly when downgrades are steep enough to require operation in a low gear. In these cases, heavy vehicles must operate at slower speeds than do passenger cars, again forming gaps ahead and queues behind in the traffic stream.

Directional and Lane Distribution

Two traffic characteristics in addition to the vehicle type distribution affect capacity, service flow rates, and LOS: directional distribution and lane distribution. Directional distribution has a dramatic impact on two-lane rural highway operation, where optimal conditions are achieved when the amount of traffic is roughly equal in each direction. Capacity analyses for multilane highways focus on a single direction of flow. Nevertheless, each direction of the highway is usually designed to accommodate the peak flow rate in the peak direction. Typically, a.m. peak traffic occurs in one direction and p.m. peak traffic occurs in the opposite direction.

Lane distribution is another factor on multilane facilities. Traffic volumes are typically not distributed evenly between lanes, because of drivers pre-positioning themselves for downstream movements (e.g., left turns, exits), vehicle performance characteristics (e.g., heavy vehicles tending to keep right), and local traffic laws (e.g., left lane restricted to passing, trucks prohibited from the left lane), among other factors. The uneven distribution results in less efficient operations than if traffic was more evenly distributed.

Driver Population

It is generally accepted that driver populations who do not use a roadway on a regular basis display characteristics different from those of motorists who are familiar with the roadway. HCM methods allow the user to make an adjustment for driver population, for system elements where driver population has made a difference in the observed capacity. This adjustment is based on user judgment, and the HCM does not provide any quantitative means for determining it.

Control Conditions

For interrupted-flow facilities, the control of the time that specific traffic flows are allowed to move is critical to capacity, service flow rates, and LOS. The most critical type of control is the traffic signal. The type of control in use, signal phasing, allocation of green time, cycle length, and the relationship with adjacent control measures all affect operations.

STOP and YIELD signs also affect capacity, but in a less deterministic way. A traffic signal designates times when each movement is permitted; however, a STOP sign at a two-way STOP-controlled intersection only designates the right-of-way to the major street. Motorists traveling on the minor street must stop to find gaps in the major traffic flow. Therefore, the capacity of minor approaches depends on traffic conditions on the major street. An all-way STOP control requires drivers to stop and enter the intersection in rotation. Capacity and operational characteristics can vary widely, depending on the traffic demands on the various approaches.

Other types of controls and regulations can significantly affect capacity, service flow rates, and LOS. Restricted curb parking can increase the number of lanes available on a street or highway. Turn restrictions can eliminate conflicts at intersections, increasing capacity. Lane use controls can allocate roadway space to component movements and can create reversible lanes. One-way street routings can eliminate conflicts between left turns and opposing traffic.

Technology and Operations

Intelligent transportation systems.

Technological strategies, commonly known as intelligent transportation systems (ITS) strategies, aim to increase the safety and performance of roadway facilities. For this discussion, ITS includes any technology that allows drivers and traffic control system operators to gather and use real-time information to improve vehicle navigation, roadway system control, or both. Research on ITS has grown significantly but cannot be considered comprehensive in terms of evaluating ITS impacts on roadway capacity and quality of service.

Arterial ITS strategies that have been shown to improve vehicular throughput or reduce vehicular delay are adaptive signal control and traffic signal interconnection. A freeway ITS strategy, ramp metering, has improved mainline throughput and speed, while incident management techniques have reduced the time required to identify and clear incidents and thus minimized the time during which capacity is reduced as well as the associated delay. Variable freeway speed limits, combined with automated speed limit enforcement, also show promise but require additional study (*8*).

Other ITS strategies seek to shift demand to alternative routes or times, thus making better use of system capacity and reducing delay on individual facilities. Techniques include parking availability signs at the entrances to downtown areas, value pricing, variable message signs, highway advisory radio, integrated corridor management, real-time travel time and incident information provided to computers and mobile phones, and real-time in-vehicle navigation systems (*8*).

Other strategies for effectively operating roadways are not inherently based on technology, although they may be supported by technology. Examples include managed lanes and highway service patrols.

Specific impacts of technology and operations strategies on roadway capacity and performance are discussed in Chapter 37, ATDM: Supplemental, where research is available to document those impacts.

Environmental Conditions

A facility's capacity can be temporarily reduced by environmental conditions, such as heavy precipitation, adverse lighting conditions, or slippery road surfaces. A number of studies addressing the capacity-reducing effects of specific environmental conditions on freeways have been conducted. The results of these studies are presented in Chapter 10, Freeway Facilities Core Methodology. For interrupted-flow facilities, capacity reductions are reflected by reductions in the saturation flow rate during periods when precipitation is falling and when roadways are wet or covered by snow or ice.

ESTIMATION OF TRAFFIC FLOW PARAMETERS

Analyzing a roadway's performance involves assigning estimated values to traffic flow parameters as a function of either time or distance. There are three common approaches to estimating traffic flow parameters:

1. Deterministic models, such as those presented in the HCM;
2. Simulation models, which take a microscopic and stochastic approach to the representation of traffic flow; and
3. Field data observations, which attempt to measure the parameters directly by data collection and analysis.

All of these approaches can only produce estimates of the parameters of interest. Each approach involves assumptions and approximations. The three approaches are bound together by the common goal of representing field conditions accurately.

On the surface, field observations appear likely to produce the most accurate representation of traffic flow. However, quantitative observations of some traffic phenomena are difficult to produce in a consistent manner that avoids subjective interpretation. There are limits to the accuracy of human observation, and instrumentation of traffic flow data collection is not practical for routine field studies, except for very simple parameters such as flow rate. Field data observations require a level of effort that often exceeds the available resources. Modeling techniques have therefore been introduced as a practical, but approximate, method of estimating required parameters. It is important that modeling techniques be based on definitions and computations that are as consistent as possible with field observations and with each other.

Vehicle trajectories are the lowest common denominator for estimating traffic flow parameters.

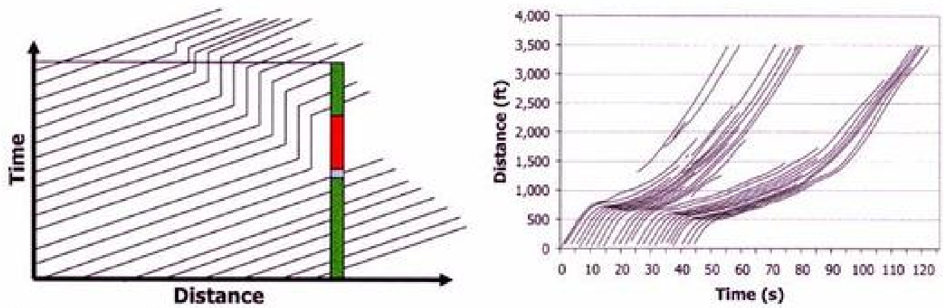
Vehicle time–space trajectories are recognized in the literature as the "lowest common denominator" for this purpose (*9*). Vehicle trajectories represent the "ground truth" that all measurement and analysis techniques attempt to represent. Microscopic simulation models create trajectories explicitly through algorithms that apply principles of traffic flow theory to the propagation of vehicles along a highway segment. Macroscopic deterministic models do not deal with trajectories at the same level of detail, but they attempt to produce an approximation of the results that would be obtained from trajectory analyses.

Field observations typically establish critical points along individual trajectories rather than complete trajectories.

With a few exceptions involving a significant research effort, field observations are not able to create complete trajectories. Instead, they attempt to establish critical points along individual trajectories. Because of its ability to create complete trajectories, simulation modeling may be viewed as a surrogate for field data collection through which the critical points on the trajectory may be established. Definition of the critical points in a manner that promotes compatibility between the analysis techniques is important.

Vehicle trajectories may be represented graphically or mathematically. The graphical representation shows the position of each vehicle in time and space as it traverses a length of the highway. Typical examples of vehicle trajectory plots are shown in Exhibit 4-11.

Exhibit 4-11
Typical Examples of Vehicle Trajectory Plots



(a) Interrupted Flow on a Signalized Approach

(b) Uninterrupted Flow on a Freeway

Exhibit 4-11(a) depicts a classic queue accumulation and release at a signalized stop line. Exhibit 4-11(b) shows a typical freeway situation in which queuing and shock waves are caused entirely by vehicle interactions and not by traffic control devices.

Three characteristics of Exhibit 4-11 are not necessarily common to all time–space representations of vehicle trajectories:

1. Time may be shown on either the vertical or the horizontal axis. Note that Exhibit 4-11(a) shows time on the vertical axis, while Exhibit 4-11(b) shows time on the horizontal axis.
2. The angular shape of the interrupted-flow trajectory curves in Exhibit 4-11(a) does not represent the acceleration and deceleration in their true forms. This shape displays an approximation of the trajectory that is appropriate for some interpretations and inappropriate for others.
3. Both plots represent a single lane of operation in which each vehicle follows its leader according to established rules. Multilane trajectory plots differ from single-lane plots in two ways. First, the first-in, first-out queue discipline can be violated in multilane situations because of overtaking. In other words, a vehicle entering a link later than its leader could leave the link earlier. Graphically, this situation is represented by trajectory lines crossing each other. Second, some vehicles might change lanes. Lane changes cannot be represented in the Exhibit 4-11 plots because distance is shown as a one-dimensional scalar quantity. Because of these complexities, multilane trajectories are much harder to analyze.

While plots such as Exhibit 4-11 provide good visual insight into vehicle operations, they do not support quantitative assessments. To develop performance measures from vehicle trajectories, the trajectories must be represented mathematically rather than visually. A mathematical representation requires development of a set of properties that are associated with each vehicle at specific points in time and space. Because of the time-step formulation of most simulation models, time rather than distance is the preferred reference point.

The key to producing performance measures that are comparable among different estimation techniques is developing a set of definitions that enforce a consistent interpretation of the vehicle trajectories. The subject of trajectory-based definitions is treated in more detail in Chapter 7, Interpreting HCM and Alternative Tool Results, and in Chapter 36, Concepts: Supplemental.

3. PEDESTRIAN MODE

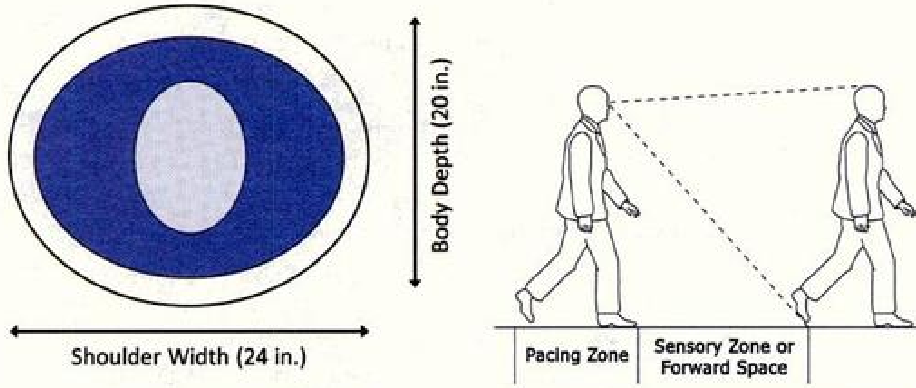
PEDESTRIAN CHARACTERISTICS

Pedestrian Space Requirements

Pedestrian facility designers use body depth and shoulder breadth for minimum space standards, at least implicitly. A simplified body ellipse of 18 in. by 24 in., enclosing an area of 2.35 ft^2 and incorporating a heavily clothed 95th percentile male and his buffer area to other pedestrians, has been used as the basic space for a single pedestrian, on the basis of 1970s data (*10*). The body ellipse area represents the practical minimum space for standing pedestrians. More recent data, accounting for increases in the body size of the U.S. population since the 1970s, suggest that an extra 2 in. of body depth is required to provide an equivalent buffer area for a U.S. pedestrian in the 2010s. This larger body ellipse of 20 in. by 24 in. encloses an area of 2.6 ft^2 (*11*) and is shown in Exhibit 4-12(a).

In contrast to a standing pedestrian, a walking pedestrian requires a certain amount of forward space. This forward space is a critical dimension, since it determines the speed of the trip and the number of pedestrians able to pass a point in a given time period. The forward space in Exhibit 4-12(b) is categorized into a pacing zone and a sensory zone (*10*).

Exhibit 4-12
Pedestrian Body Ellipse for Standing Areas and Pedestrian Walking Space Requirement



(a) Pedestrian Body Ellipse (b) Pedestrian Walking Space Requirement

Sources: Adapted from Fruin (*10*) and *TCRP Report 165: Transit Capacity and Quality of Service Manual*, 3rd edition (*11*).

Walking Speed

Factors affecting walking speed.

Pedestrian walking speed is highly dependent on the characteristics of the walking population. The proportion of elderly pedestrians (65 years old or more) and children in the population, as well as trip purpose, affects walking speed. A national study (*12*) found the average walking speed of younger (age 13–60) pedestrians crossing streets to be significantly different from that of older pedestrians (4.74 ft/s versus 4.25 ft/s, respectively). The 15th percentile speed, the speed used in the *Manual on Uniform Traffic Control Devices* (*13*) for timing the pedestrian clearance interval at traffic signals, was 3.03 ft/s for older pedestrians and 3.77 ft/s for younger pedestrians. Exhibit 4-13 shows these relationships.

Exhibit 4-13
Observed Older and Younger Pedestrian Walking Speed Distribution at Unsignalized Intersections

Source: Adapted from *TCRP Report 112/NCHRP Report 562* (*12*).

Pedestrian Start-Up Time

At crosswalks located at signalized intersections, pedestrians may not step off the curb immediately when the WALK indication appears, in part because of perception–reaction time and in part to make sure that no vehicles have moved or are about to move into the crosswalk area. This hesitation is termed *pedestrian start-up time* and is used in evaluating pedestrian crosswalks at traffic signals.

PEDESTRIAN FLOW PARAMETERS

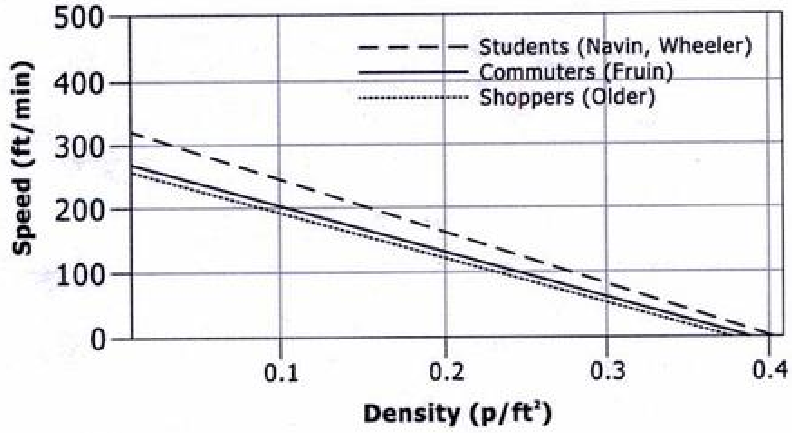
Speed, Flow, and Density Relationships

Speed–Density Relationships

The fundamental relationship between speed, density, and volume for directional pedestrian flow on facilities with no cross flows, where pedestrians are constrained to a fixed walkway width (because of walls or other barriers), is analogous to that for vehicular flow. As volume and density increase, pedestrian speed declines. As density increases and pedestrian space decreases, the degree of mobility afforded to the individual pedestrian declines, as does the average speed of the pedestrian stream.

Exhibit 4-14 shows the relationship between speed and density for three pedestrian classes.

Exhibit 4-14
Relationships Between Pedestrian Speed and Density



Source: Adapted from Pushkarev and Zupan (*14*).

Flow–Density Relationships

Similarities of pedestrian movement to vehicular traffic.

The relationship among density, speed, and directional flow for pedestrians is similar to that for vehicular traffic streams and is expressed in Equation 4-11:

Equation 4-11

$$v_{ped} = S_{ped} \times D_{ped}$$

where

v_{ped} = unit flow rate (p/min/ft),

S_{ped} = pedestrian speed (ft/min), and

D_{ped} = pedestrian density (p/ft²).

The flow variable in Equation 4-11 is the unit width flow, defined as the pedestrians per minute per unit width (e.g., foot) of walkway. An alternative, more useful, expression uses the reciprocal of density, or *space*:

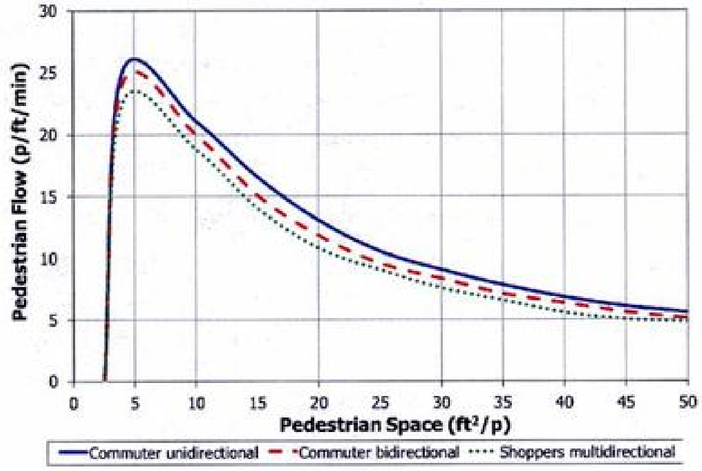
Equation 4-12

$$v_{ped} = \frac{S_{ped}}{M}$$

where M = pedestrian space (ft²/p).

The basic relationship between flow and space is illustrated in Exhibit 4-15:

Exhibit 4-15
Relationships Between Pedestrian Flow and Space



Source: Fruin (*10*).

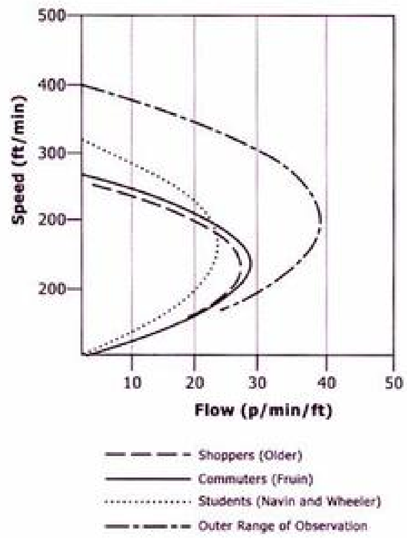
The conditions at maximum flow represent the capacity of the walkway facility. From Exhibit 4-15, it is apparent that all observations of maximum unit flow fall within a narrow range of density, with the average space per pedestrian varying between 5 and 9 ft²/p. Even the outer range of these observations indicates that maximum flow occurs at this density, although the actual flow in this study is considerably higher than in the others. As space is reduced to less than 5 ft²/p, the flow rate declines precipitously. All movement effectively stops at the minimum space allocation of 2 to 4 ft²/p.

These relationships show that pedestrian traffic can be evaluated quantitatively by using basic concepts similar to those of vehicular traffic analysis. At flows near capacity, an average of 5 to 9 ft²/p is required for each moving pedestrian. However, at this level of flow, the limited area available restricts pedestrian speed and freedom to maneuver.

Speed–Flow Relationships

Exhibit 4-16 illustrates the relationship between pedestrian speed and flow. These curves, similar to vehicle flow curves, show that when there are few pedestrians on a walkway (i.e., low flow levels), there is space available to choose higher walking speeds. As flow increases, speeds decline because of closer interactions among pedestrians. When a critical level of crowding occurs, movement becomes more difficult, and both flow and speed decline.

Exhibit 4-16
Relationships Between Pedestrian Speed and Flow

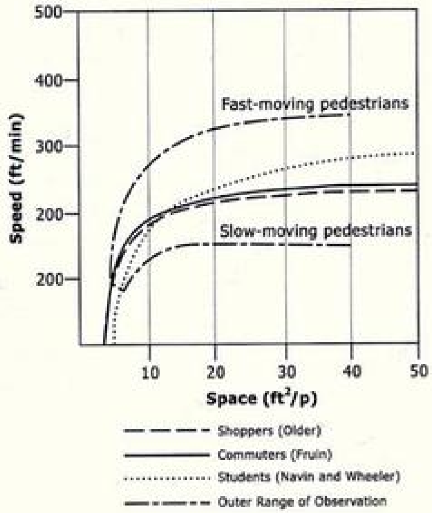


Source: Adapted from Pushkarev and Zupan (*14*).

Speed–Space Relationships

Exhibit 4-17 also confirms the relationships of walking speed and available space. The outer range of observations shown in Exhibit 4-17 indicates that at an average space of less than 15 ft²/p, even the slowest pedestrians cannot achieve their desired walking speeds. Faster pedestrians, who walk at speeds of up to 350 ft/min, are not able to achieve that speed unless the average space is 40 ft²/p or more.

Exhibit 4-17
Relationships Between Pedestrian Speed and Space



Source: Adapted from Pushkarev and Zupan (*14*).

Flow on Urban Sidewalks and Walkways

While the fundamental relationships described above hold for pedestrians on constrained facilities with linear flow (e.g., bridges and underground passageways), they are complicated on urban sidewalks and walkways by other factors. In particular, cross flows, stationary pedestrians, and the potential for spillover outside of the walkway affect pedestrian flows on these facilities. Quantitative research describing the effects of these factors on pedestrian flow is limited, but the effects are described qualitatively here.

Cross flows of pedestrians entering or exiting adjacent businesses, getting on or off buses at bus stops, or accessing street furniture are typical on most urban pedestrian facilities. Where pedestrian volumes are high, these cross flows will disrupt the speed–flow relationships described above, resulting in lower pedestrian speeds at equivalent flow rates. In addition, stationary pedestrians will be present on most urban pedestrian facilities as pedestrians stop within the walkway to talk, to look in store windows, or for other reasons. Stationary pedestrians reduce pedestrian flow by requiring pedestrians to maneuver around them and decreasing the available width of the walkway.

The furniture zone is the portion of the sidewalk dedicated to pedestrian amenities (e.g., benches) and is not intended to serve pedestrian flow.

Finally, in situations where pedestrians are not physically confined within the walkway, pedestrians will often choose to walk outside of the prescribed walking area (e.g., walk in the furniture zone or street) when high densities are reached. Thus, in practice, facilities will often break down, with pedestrians spilling over into the street, before the maximum flow rate shown in Exhibit 4-15 is reached.

The result of the combination of factors described above is that many pedestrian facilities will reach effective failure at densities far less than the facility's capacity. Analysis of pedestrian facilities should take into consideration local conditions, including the presence of destinations along the facility that contribute to cross-flows and stationary pedestrians, as well as opportunities for pedestrians to spill over onto adjacent facilities.

Pedestrian Type and Trip Purpose

The analysis of pedestrian flow is generally based on the mean, or average, walking speeds of groups of pedestrians. Within any group, or among groups, there can be considerable differences in flow characteristics due to trip purpose, adjacent land use, type of group, age, mobility, cognitive ability, and other factors.

Pedestrians going to and from work and using the same facilities day after day walk at higher speeds than do shoppers, as was shown in Exhibit 4-14. Older or very young persons tend to walk more slowly than do other groups. Shoppers not only tend to walk more slowly than do commuters but also can decrease the effective walkway width by stopping to window-shop and by carrying shopping bags. The analyst should adjust for pedestrian behavior that deviates from the regular patterns represented in the basic speed, volume, and density curves.

Influences of Pedestrians on Each Other

Photographic studies show that pedestrian movement on sidewalks is affected by other pedestrians, even when space is more than 40 ft^2/p. At 60 ft^2/p, pedestrians have been observed walking in a checkerboard pattern rather than directly behind or alongside each other. The same observations suggest the necessity of up to 100 ft^2/p before completely free movement occurs without conflicts, and that at 130 ft^2/p, individual pedestrians are no longer influenced by others (*15*). Bunching or platooning does not disappear until space is about 500 ft^2/p or higher.

Maintaining flow in the minor (opposing) direction.

Another issue is the ability to maintain flow in the minor direction on a sidewalk when it is opposed by a major pedestrian flow. For pedestrian streams of roughly equal flow in each direction, there is little reduction in the capacity of the walkway compared with one-way flow, because the directional streams tend to separate and occupy a proportional share of the walkway. However, if the directional split is 90% versus 10% and space is 10 ft^2/p, capacity reductions of about 15% have been observed. The reduction results from the minor flow using more than its proportionate share of the walkway.

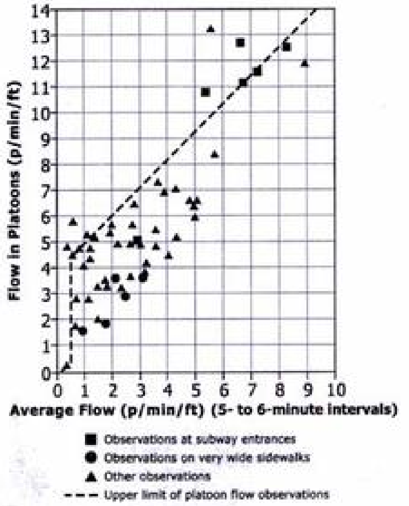
Opposing flows on stairways.

Similar but more severe effects are seen with stairways. In contrast to their behavior on a level surface, people tend to walk in lines or lanes in traversing stairs. A small reverse flow occupies one pedestrian lane (30 in.) of the stairway's width. For a stairway 60 in. (5 ft) wide, a small reverse flow could consume half its capacity (*11*).

Cross flows.

A pedestrian's ability to cross a pedestrian stream is impaired at space values less than 35 ft^2/p, as shown in Exhibit 4-18. Above that level, the probability of stopping or breaking the normal walking gait is nearly zero. Below 15 ft^2/p, almost every crossing movement encounters a conflict. Similarly, the ability to pass slower pedestrians is unimpaired above 35 ft^2/p, but it becomes progressively more difficult as space allocations drop to 18 ft^2/p, the point at which passing becomes virtually impossible (*10, 16*).

Exhibit 4-21
Relationship Between Platoon Flow and Average Flow



Source: Adapted from Pushkarev and Zupan (*14*).

CAPACITY CONCEPTS

Pedestrian Circulation Facilities

Pedestrian capacity on facilities designed for pedestrian circulation is typically expressed in terms of *space* (square feet per pedestrian) or *unit flow* (pedestrians per minute per foot of walkway width). The relationship between space and flow was illustrated in Exhibit 4-15. Capacity occurs when the maximum flow rate is achieved. Typical values for pedestrian circulation facilities are as follows:

- Walkways with random flow, 23 p/min/ft;
- Walkways with platoon flow (average over 5 min), 18 p/min/ft;
- Cross-flow areas, 17 p/min/ft (sum of both flows); and
- Stairways (up direction), 15 p/min/ft.

As shown in Exhibit 4-16, average pedestrian speeds at capacity are about half the average speed obtained under less congested conditions. As a result, pedestrian circulation facilities are typically not designed for capacity but rather for a less congested condition that achieves lower pedestrian throughput but that provides pedestrians with greater opportunity to travel at their desired speed with minimal conflicts with other pedestrians. Moreover, as described above under "Flow on Urban Sidewalks and Walkways," pedestrian facilities often break down before maximum flow rates are achieved, as a result of pedestrian spillover outside of the walkway into the furniture zone or roadway.

Pedestrian Queuing Facilities

Pedestrian capacity on facilities designed for pedestrian queuing is expressed in terms of space (square feet per pedestrian). In a queuing area, the pedestrian stands temporarily while waiting to be served. In dense, standing crowds, there is little room to move, but limited circulation is possible as the average space per pedestrian increases. Queuing at or near capacity (2 to 3 ft^2/p) typically occurs only in the most crowded elevators or transit vehicles. Queuing on sidewalks, waiting to cross at street corners, is more typically in the 3- to 6-ft^2/p range, which is still crowded but provides some internal maneuverability.

4. BICYCLE MODE

BICYCLE FLOW PARAMETERS

Although bicyclists are not as regimented as vehicles, they tend to operate in distinct lanes of varying widths when space is available. The capacity of a bicycle facility depends on the number of effective lanes used by bicycles. Shared-lane facilities typically have only one effective lane, but segregated facilities such as bicycle lanes, shoulder bikeways, pathways, and cycle tracks may have more than one effective lane, depending on their width. When possible, an analysis of a facility should include a field evaluation of the number of effective lanes in use. When this is not possible, or when future facilities are planned, a standard width for an effective bicycle lane is 3.5 to 4 ft (*17, 18*). The American Association of State Highway and Transportation Officials recommends that off-street bicycle paths be 10 ft wide (*17*).

The effective bicycle lane width consists of the space used by a bicyclist while riding, plus shy distance to a passing bicyclist. It does not include shy distance to the curb and other elements that influence overall bicycle lane width.

Research demonstrates that three-lane bicycle facilities operate more efficiently than two-lane bicycle facilities, affording considerably better quality of service to users (*19*). The improved efficiency is due primarily to increased opportunities for passing and for maneuvering around other bicyclists and pedestrians. This reinforces the value of determining the number of effective lanes as the principal input for analyzing a bicycle facility.

A study that compared mean bicycle speeds with bicycle flow rates over 5-min periods found at most a minor effect of flow rates on speed, for flow rates ranging from 50 to 1,500 bicycles/h. When the analysis focused on platoons of bicycles with headways less than 5 s, bicycle speeds trended slightly lower as flow rates increased (*20*).

Most bicyclists travel on facilities that are shared with automobiles. In these circumstances, bicycle flow is significantly affected by the characteristics of surrounding automobile flow. Bicyclists often must wait behind queues of automobiles. Even where bicyclists may pass such queues, they are often forced to slow because the available space in which to pass is too constrained to allow free-flow speeds to occur.

Data collected for more than 400 adult bicyclists riding on uninterrupted multiuse segments showed an average speed of 12.8 mi/h (*19*). However, the speed of an individual bicyclist varies considerably from this average on the basis of trail conditions, age, fitness level, and other factors. Exhibit 4-22 shows how bicyclist speed varies with age, on the basis of Danish data. Data are for typical bicyclists on flat terrain.

Exhibit 4-22
Age Effects on Bicyclist Speed

Source: Danish Road Directorate (*21*).

Flow rates of bicyclists usually vary over the course of an hour. As described above for automobiles, HCM analyses typically consider the peak 15 min of flow during the analysis hour. Because inputs to HCM procedures are typically expressed in terms of hourly demands, the HCM uses the PHF, shown by Equation 4-1, to convert an hourly volume into a peak 15-min flow rate. Data for bicycles on eight trails, recorded over three separate time periods for each trail, showed PHFs ranging from 0.70 to 0.99, with an average of 0.85 (*19*).

CAPACITY CONCEPTS

Because service quality deteriorates at flow levels well below capacity, the concept of capacity has little utility in the design and analysis of bicycle paths and other facilities. Capacity is rarely observed on bicycle facilities. Values for capacity, therefore, reflect sparse data, generally from Europe and generally extrapolated from flow rates over time periods substantially less than 1 h.

One study reported capacity values of 1,600 bicycles/h/ln for two-way bicycle facilities and 3,200 bicycles/h/ln for one-way facilities. Both values were for exclusive bicycle facilities operating under uninterrupted-flow conditions (*22*). Other studies have reported values in the range of 1,500 to 5,000 bicycles/h/ln for one-way uninterrupted-flow facilities (*19*).

Danish guidelines suggest that bicycle capacity is normally only relevant at signalized intersections in cities and that a rule of thumb for the capacity of a two-lane cycle track is 2,000 bicycles/h under interrupted-flow conditions (i.e., 1,000 bicycles/h/ln) (*23*). The HCM recommends a saturation flow rate of 2,000 bicycles/h/ln for a one-direction bicycle lane under interrupted-flow conditions, which is equivalent to a capacity of 1,000 bicycles/h/ln when the bicycle lane receives a green indication during 50% of the signal cycle.

DELAY

Delay is an important performance measure for bicyclists on interrupted-flow system elements. This is true because delay increases travel time and because the physical exertion required to accelerate a bicycle makes stopping or slowing undesirable and tiring. The difficulty involved in stopping and starting a bicycle often makes it appropriate to assess not only the control delay incurred by bicyclists but also the number of stops that bicyclists are required to make to traverse a facility. For example, a facility with STOP signs every several hundred feet will require bicyclists to stop frequently and thus will provide lower capacity and quality of service to users.

5. TRANSIT MODE

BUS SPEED PARAMETERS

Bus speeds on urban streets are influenced by the same factors that influence automobile speeds, particularly the delay caused by traffic signals and other forms of intersection control. As heavy vehicles, buses accelerate and decelerate more slowly than passenger cars. In addition, many bus-specific factors influence speed; these involve operations, vehicle, roadway, and passenger characteristics. These factors are described below.

Material in this section generally refers to buses but is also applicable to streetcars and light rail vehicles operating on urban streets, except where specifically stated otherwise.

Bus Operations

Stop Spacing

Unlike other urban street users, most transit vehicles (except for express buses) stop periodically so that passengers may board and alight. Each stop introduces up to seven forms of delay (*11*):

- *Deceleration delay,* as a bus slows down approaching a stop;
- *Bus stop failure,* which occurs when a bus arriving at a stop finds all loading areas occupied and must wait for space to become available;
- *Boarding lost time,* time spent waiting for passengers to travel from their waiting position at the bus stop to the bus door;
- *Passenger service time,* time for passenger loading, unloading, and fare payment, as well as time spent opening and closing the doors;
- *Traffic signal delay,* time spent waiting for a green light after serving passengers at a stop on the near side of an intersection (i.e., a *near-side* stop);
- *Reentry delay,* time spent waiting for a gap in traffic to leave the bus stop; and
- *Acceleration delay,* as a bus speeds up to its running speed on the street.

Increasing the stop spacing reduces the number of occurrences of these types of delay, which results in a net increase in speeds. (Passenger service times may increase, though, as passenger activity is concentrated at fewer stops.) Reported travel time savings due to stop consolidation have ranged from 4.4% to approximately 19% (*11*).

The ability to increase stop spacing depends on many factors, including the quality of the pedestrian network in the area, the locations of transit trip generators and transfer points, and driveway and curb parking locations (*11*).

Stop Location

Bus stop location affects bus speeds by influencing the amount of delay induced by other roadway users—particularly right-turning vehicles—on buses trying to access a bus stop. All other things being equal, far-side stops produce less delay than near-side stops, with the delay benefit increasing with increasing intersection volume-to-capacity ratio and increasing traffic signal cycle length.

However, other factors, such as those listed above for increasing stop spacing, must also be weighed when relocation of stops is considered (*24*).

Stopping Patterns

When a street is used by a high volume of buses, having all buses stop at the same set of stops can create bus congestion and slow down speeds. A *skip-stop* stopping pattern, under which buses are divided into groups that share a certain set of stops, can substantially improve overall bus speeds, as well as bus facility capacity, with the trade-off of making it more difficult for nonregular passengers to find their bus stop. *Platooning* occurs when buses travel together, like cars of a train, along a roadway. Platoons can be developed by traffic signals or can be deliberately formed through careful scheduling and field supervision, although the latter is rare in North America. Platooning minimizes bus passing activity and thus results in higher overall speeds (*11*).

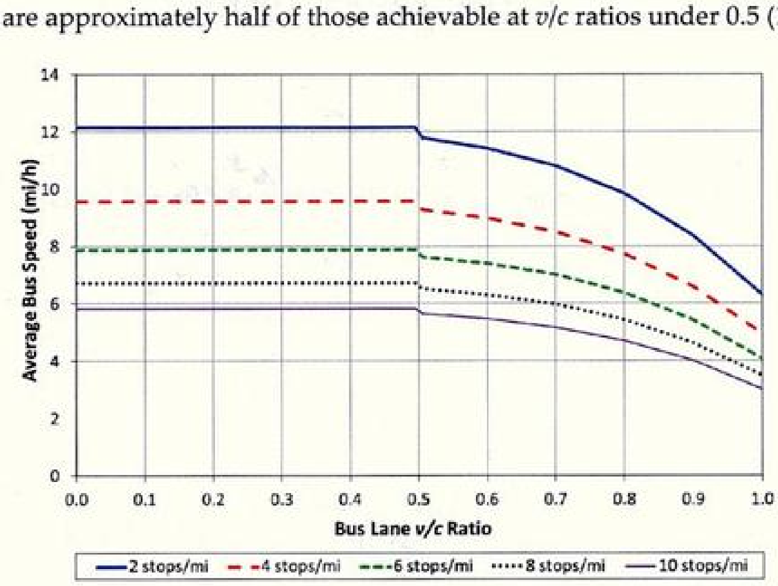
Fare Payment

The time required for passengers to pay a fare affects the passenger service time at stops. The average time needed to board a low-floor bus with no or prepaid (e.g., bus pass or free transfer) fare payment is 1.75 s/passenger. The various types of fare payment methods (e.g., cash, tickets, tokens, magnetic-stripe cards, smart cards) have service times associated with them that increase the service time by up to 3.25 s/passenger, on average, above the base level (*11*).

Service Planning and Scheduling

Bus speeds along an urban street decline when 50% or more of the hourly bus capacity is utilized, as illustrated in Exhibit 4-23. As the number of buses using a bus lane increases, there is a greater probability that one bus will delay other buses, either by using the remaining space at a bus stop or by requiring bus passing and weaving maneuvers. At a volume-to-capacity (v/c) ratio of 1.0, bus speeds are approximately half of those achievable at v/c ratios under 0.5 (*11*).

Exhibit 4-23
Illustrative Bus Speed Relationship to Bus Lane *v/c* Ratio



Source: *TCRP Report 165: Transit Capacity and Quality of Service Manual*, 3rd edition (*11*).
Notes: Assumes 30-s dwell times, 25-mi/h running speed, central business district bus lane with right-turn delays, and typical signal timing. *v/c* ratio = volume-to-capacity ratio.

Passenger Loads

On buses where demand exceeds seating capacity, causing some passengers to stand, more passenger service time (typically 0.5 s/passenger) is required at stops, because standing passengers must push toward the back of the bus to allow other passengers to board and because alighting passengers take longer to get to a door (*11*).

Vehicle Characteristics

Low-floor buses are in common use and eliminate the need for passengers to ascend and descend steps, which would otherwise typically add 0.5 s to each passenger's boarding or alighting time. Wide bus doors allow more passengers to board and alight simultaneously (*11*). Different types of buses have different acceleration characteristics, which influence the amount of acceleration delay incurred when a bus stops.

Roadway Infrastructure

Refer to TCRP Report 183 *(24) for illustrations and guidance on appropriate locations for transit preferential treatments.*

Roadway infrastructure treatments are physical treatments designed to give transit vehicles a travel time advantage over motorized vehicle traffic or to avoid delays caused by other roadway users. The following are common infrastructure treatments used on urban streets:

- *Exclusive bus lanes.* One or more lanes reserved for the full- or part-time use of buses. They restrict or eliminate interactions with other roadway users that slow down buses. With typical signal timing, bus lanes can provide a 1.0- to 1.8-min/mi speed benefit (*11*).
- *Queue jumps.* Short bus lane sections (often shared with a right-turn lane), in combination with an advance green indication for the lane, that allow buses to move past queues of cars at signals. They primarily provide a bus delay benefit at high intersection volume-to-capacity ratios (*24*).
- *Boarding islands.* A raised area within the roadway that allows buses to stop to serve passengers from an inside lane, thus avoiding delays associated with curb-lane travel (e.g., parking, deliveries, right-turning vehicles yielding to pedestrians) (*24*).
- *Curb extensions.* An extension of the sidewalk to the edge of the travel or bicycle lane (e.g., by removing on-street parking). Curb extensions eliminate reentry delay by allowing buses to stop in their travel lane. At the range of curb volumes appropriate for curb extensions (under 500 veh/h), they can save buses up to 4 s of delay per stop on average (*11*).

Traffic Operations

Traffic operations treatments are changes in the roadway's traffic control that are designed to give transit vehicles a travel time advantage over motorized vehicle traffic or to avoid delays caused by other roadway users. The following are common operations treatments used on urban streets:

- *Transit signal priority (TSP).* TSP modifies the traffic signal timing to reduce bus delay while maintaining signal coordination and overall traffic signal cycle length. Systems of intersections equipped with TSP have produced a wide range of results, from no change in corridor-level travel times up to an approximate 20% reduction in travel times. In general, bus travel time variability is reduced by TSP. The ability to obtain corridor-level reductions in travel times depends in part on whether bus schedules are changed to take advantage of TSP, as well as whether a bus is able to pass through the next downstream signal or simply arrives earlier on red (and thus obtains no net benefit) (*24*).

- *Movement restriction exemptions.* Buses are allowed to make movements at locations where other vehicles are not allowed to. This treatment allows buses to travel more direct routes; the time saved depends on the length of and the delay associated with the alternative route (*11*).
- *General traffic movement restrictions.* Motorized vehicles may be prohibited from making movements (e.g., left turns) during times of day when vehicles stopped to make turns would unduly delay other roadway users, including buses. There can also be associated safety and reliability benefits (*24*).
- *Parking restrictions.* Parking restrictions can be used to free roadway space for other uses, such as queue-jump lanes or part-time bus lanes, or to eliminate the traffic delays caused by high parking turnover. The impacts on adjacent land uses must be carefully considered, and regular enforcement is required to ensure that buses receive full benefit (*11*).

Passenger Characteristics

Passenger Distribution

The distribution of boarding passengers among bus stops affects the passenger service time of each stop. If passenger boardings are concentrated at one stop along a street, that street's bus capacity will be lower than if boardings were more evenly distributed. With a lower capacity, fewer scheduled buses in an hour will bring about bus interactions that affect bus speeds.

Strollers, Wheelchairs, and Bicycles

Passenger service times are longer for passengers with strollers or using wheelchairs, particularly with high-floor buses when a lift must be deployed. A passenger using a bicycle rack mounted to the bus will also cause service time to increase, except when other passengers are still being served after the bicycle has been secured. In many cases, these events are sufficiently infrequent to be indistinguishable from the normal variation in passenger demands and service times at a bus stop.

CAPACITY CONCEPTS

Differences Between Transit and Highway Capacity

Transit capacity is different from highway capacity: it deals with the movement of both people and vehicles, it depends on the size of the transit vehicles and how often they operate, and it reflects the interaction of passenger traffic and vehicle flow. Transit capacity depends on the operating policy of the transit agency, which specifies service frequencies and allowable passenger loadings. Accordingly, the traditional concepts applied to highway capacity must be adapted and broadened.

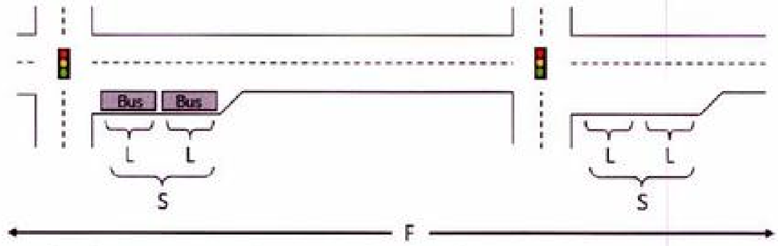
Two key characteristics differentiate transit from the automobile in terms of availability and capacity. First, automobiles have widespread access to roadway facilities, whereas transit service is available only in certain locations and during certain times. Second, roadway capacity is available 24 h/day once it is constructed, but transit passenger capacity is limited by the number of transit vehicles operated at a given time.

The HCM distinguishes between vehicle and person capacity. *Vehicle capacity* reflects the number of buses that pass a given location during a given time period and is thus most closely analogous to automobile capacity. *Person capacity* reflects the number of people that can be carried past a given location during a given time period under specified operating conditions, without unreasonable delay, hazard, or restriction, and with reasonable certainty.

Vehicle Capacity

Vehicle (bus) capacity is commonly determined for three locations along an urban street: individual loading areas (berths) at bus stops, individual bus stops, and an urban street facility, as illustrated in Exhibit 4-24. Each location directly influences the next. The vehicle capacity of a bus stop is controlled by the vehicle capacities of the loading areas, and the vehicle capacity of the urban street facility is controlled by the vehicle capacity of the critical stop within the facility.

Exhibit 4-24
Bus Loading Areas, Stops, and Facilities



L = loading area, S = bus stop, F = bus facility

Source: *TCRP Report 165: Transit Capacity and Quality of Service Manual,* 3rd edition (*11*).

Loading Area Capacity

The following are the main elements determining loading area capacity (*11*):

- *Dwell time,* the sum of passenger service time, boarding lost time, and the time required to open and close the bus doors.
- *Dwell time variability,* the difference in dwell times among different buses using the stop over the course of an hour.
- *Traffic signal timing,* affecting the proportion of time available in an hour for buses to enter (far-side) or exit (near-side) bus stops.
- *Failure rate,* a design input reflecting the desired probability that one bus will arrive at a bus stop only to find all loading areas already occupied. Capacity is improved with higher design failure rates, but speed and reliability suffer when buses must wait in the street to enter a stop.

- *Clearance time,* the sum of the time required for a bus to start up and travel its own length (freeing space for the next bus) and reentry delay.

Bus Stop Capacity

Bus stops consist of one or more loading areas. When a bus stop consists of a single loading area, its capacity is equivalent to the loading area capacity. However, when a bus stop consists of multiple loading areas, the number of loading areas and the design of the loading areas influence its capacity.

Effective loading areas.

Most on-street bus stops are *linear* bus stops, where the first bus to arrive occupies the first loading area, the second bus occupies the second loading area, and so on. Each additional linear loading area at a bus stop is less efficient than the one before it because buses stopped at one of the rear loading areas may block access to available loading areas in front of them.

Efficiency drops significantly above three loading areas. Efficiency is also affected by whether buses stop in or out of the travel lane and by whether platooning occurs (*11*).

Bus Facility Capacity

Bus facility capacity is constrained by the bus stop with the lowest capacity along the facility, or *critical stop*. This stop is usually the bus stop with the longest dwell time. However, a near-side stop at an intersection with high right-turning volumes (particularly in combination with high conflicting crosswalk volumes) or a stop before or after a signalized intersection approach with a short green time could also be the critical stop (*11*).

Person Capacity

For HCM analysis purposes, person capacity is typically calculated only at the facility level. It is determined by three main factors (*11*):

1. *Vehicle capacity,* which determines the maximum number of buses that can be scheduled to use the bus facility over the course of an hour;
2. *Agency policy,* which sets loading standards for buses and determines how frequently buses operate (which is usually less than the maximum possible frequency); and
3. *Passenger demand characteristics,* reflected by a PHF.

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CHAPTER 5
QUALITY AND LEVEL-OF-SERVICE CONCEPTS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

OVERVIEW

There are many ways to measure the performance of a transportation facility or service—and many points of view that can be considered in deciding which measurements to make. The agency operating a roadway, automobile drivers, pedestrians, bicyclists, bus passengers, decision makers, and the community at large all have their own perspectives on how a roadway or service should perform and what constitutes "good" performance. As a result, there is no one right way to measure and interpret performance.

Quality of service describes how well a transportation facility or service operates from the traveler's perspective. *Level of service* (LOS) is a quantitative stratification of a performance measure or measures representing quality of service. The LOS concept facilitates the presentation of results through the use of a familiar A (best) to F (worst) scale. LOS for a given mode on a given transportation system element is defined by one or more *service measures*. Service measures are identified from the range of performance measures that the *Highway Capacity Manual* (HCM) can estimate as the measures that (*a*) best describe operations, (*b*) best reflect the traveler perspective, and (*c*) are useful to roadway operating agencies.

CHAPTER ORGANIZATION

Three overarching concepts—quality of service, LOS, and service measures—are the subjects of Chapter 5:

- Section 2 lists the variety of factors that affect traveler perceptions of service quality and contrasts them with the topic areas that are covered in the HCM.
- Section 3 introduces the LOS concept, describes how to apply LOS as part of an analysis, and emphasizes the need to consider additional performance measures to obtain a full picture of operating conditions.
- Section 4 describes how service measures are selected, explains how LOS F is defined, and introduces the service measures used in the HCM for each system element and mode.

2. QUALITY OF SERVICE

Quality of service defined.

Quality of service describes how well a transportation facility or service operates from a traveler's perspective. Quality of service can be assessed in a number of ways. Among them are directly observing factors perceivable by and important to travelers (e.g., speed or delay), surveying travelers, tracking complaints and compliments about roadway conditions, forecasting traveler satisfaction by using models derived from past traveler surveys, and observing services not directly perceived by travelers (e.g., average incident clearance time) that affect measures they can perceive (e.g., speed, arrival time at work).

Factors that influence traveler-perceived quality of service include

- Travel time, speed, and delay;
- Number of stops incurred;
- Travel time reliability;
- Maneuverability (e.g., ease of lane changing, percent time-spent-following other vehicles);
- Comfort (e.g., bicycle and pedestrian interaction with and separation from traffic, transit vehicle crowding, pavement quality);
- Convenience (e.g., directness of route, frequency of transit service);
- Safety (actual or perceived);
- User cost;
- Availability of facilities and services;
- Facility aesthetics; and
- Information availability (e.g., highway wayfinding signage, transit route and schedule information).

The HCM provides tools for measuring the multimodal operations aspects of quality of service.

The HCM's scope, measuring the multimodal performance of highway and street facilities, is narrower than the quality-of-service aspects listed above. As discussed in Chapter 1, HCM User's Guide, companion documents to the HCM address highway safety, roadway design, and wayfinding signage, among other topics. The HCM focuses particularly on the travel time, speed, delay, reliability, maneuverability, and comfort aspects of quality of service, although a limited number of the HCM's performance measures address some of the other aspects listed above.

LOS is an important tool used by the HCM to stratify quality of service.

The HCM provides a variety of performance measures in Volumes 2 and 3 to assess the quality of service of transportation system elements. These measures can be directly observed in the field or estimated from related field-observed factors. LOS is the stratification of one or more performance measures selected to represent quality of service and is the topic of the next section.

3. LEVEL OF SERVICE

DEFINITION

LOS is a quantitative stratification of a performance measure or measures representing quality of service. The measures used to determine LOS for transportation system elements are called *service measures*. The HCM defines six levels of service, ranging from A to F, for each service measure or combination of service measures. LOS A represents the best operating conditions from the traveler's perspective and LOS F the worst. For cost, environmental impact, and other reasons, roadways are typically designed not to provide LOS A conditions during peak periods but instead to provide some lower LOS that balances individual travelers' desires against society's desires and financial resources. Nevertheless, during low-volume periods of the day, a system element may operate at LOS A.

LOS defined.

LOS is measured on an A–F scale. LOS A represents the best operating conditions from a traveler's perspective.

USAGE

LOS is used to translate complex numerical performance results into a simple A–F system representative of travelers' perceptions of the quality of service provided by a facility or service. Practitioners and decision makers alike must understand that the LOS letter result hides much of the complexity of facility performance. This feature is intended to simplify decision making on whether facility performance is generally acceptable and whether a future change in performance is likely to be perceived as significant by the general public. The language of LOS provides a common set of definitions that transportation engineers and planners can use to describe operating conditions; however, the appropriate LOS for a given system element in the community is a decision for local policy makers. One reason for the widespread adoption of the LOS concept by transportation agencies is the concept's ability to communicate roadway performance to nontechnical decision makers. However, LOS has other strengths and weaknesses, described below, that both analysts and decision makers need to be mindful of.

LOS is a useful and widely adopted tool for communicating roadway performance to laypersons and decision makers. However, its strengths and weaknesses should be kept in mind.

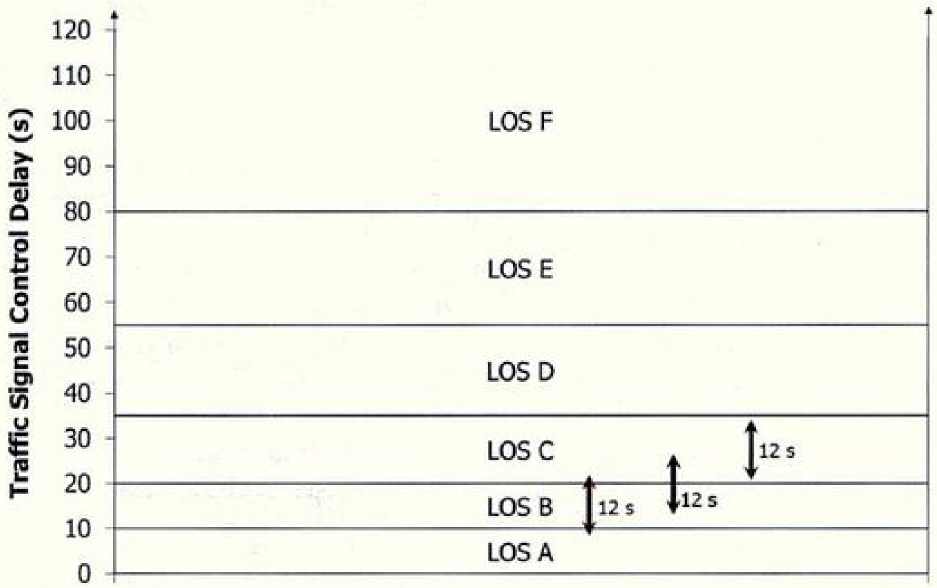
Understanding the Step Function Nature of LOS

LOS is a step function. An increase in average control delay of 12 s at a traffic signal, for example, may result in no change in LOS, a drop of one level, or even a drop of two levels, depending on the starting value of delay, as illustrated in Exhibit 5-1.

A step function provides a constant result through a range of input values and then changes abruptly to provide a new constant result after a threshold input value is reached.

From a traveler perception standpoint, the condition shown in Exhibit 5-1 is not necessarily inconsistent. A change of LOS indicates that roadway performance has transitioned from one range of traveler-perceivable conditions to another range, while no change in LOS indicates that conditions have remained within the same performance range as before. Service measure values indicate where conditions lie within a particular performance range. Because a small change in a service measure (e.g., a 2-s change in delay) can result in a change from one LOS to another, the LOS letter result can imply a more significant or perceptible change than actually occurred.

Exhibit 5-1
Example of the Step Function Nature of LOS



Identical changes in the service measure value may result in no change in LOS or a change of one or more levels of service, depending on how close the starting value is to a LOS threshold.

Defining performance standards on the basis of LOS (or any fixed numerical value) means that small changes in performance can sometimes result in the standard being exceeded, when a facility is already operating close to the standard.

This aspect of LOS can be a particularly sensitive issue when transportation agencies define their operational performance standards solely by using LOS. The definition of any fixed standard, whether numerically or as a LOS letter, always entails the possibility that a small change in performance may trigger the need for potentially costly improvements.

Variability of the Inputs to LOS

Although computer software that implements HCM methodologies can sometimes report results to many decimal places, three major sources of uncertainty influence service measure values and, thus, the LOS result:

Section 2 of Chapter 7, Interpreting HCM and Alternative Tool Results, discusses sources of uncertainty and their impacts on analysis results in more detail.

1. The models used to estimate service measure values have confidence intervals associated with their outputs.
2. The models may, in turn, rely on the output of other models that have their own associated confidence intervals.
3. The accuracy of input variables, such as demand flow rate, is taken to be absolute when, in fact, there is a substantial stochastic (i.e., random) variation around the measured values.

Models provide a best estimate of service measure values, but the "true" value likely lies within a confidence interval range above or below the estimated value.

Thus, any reported service measure value, whether resulting from an HCM methodology, an alternative tool, or field measurement, potentially has an associated range within which the "true" value lies. The LOS concept helps to downplay the implied accuracy of a numerical result by presenting a range of service measure results as being reasonably equivalent from a traveler's point of view. Nevertheless, the variability issues also mean that the "true" LOS value may be different from the one predicted by a methodology. In addition, for any given set of conditions, different travelers may perceive their LOS to be different from one another, as well as different from the LOS estimated by an HCM method. One way of thinking about reported service measure values and the corresponding LOS result is that they are the statistical "best estimators" of conditions and aggregate traveler perception.

Beyond LOS F

The HCM does not subdivide LOS F, but several measures are available to describe the severity of a LOS F condition.

The HCM uses LOS F to define operations that have either broken down (i.e., demand exceeds capacity) or have reached a point that most users would consider unsatisfactory, as described by a specified service measure value (or combination of service measure values). However, analysts may be interested in knowing just how bad the LOS F condition is, particularly for planning applications where different alternatives may be compared. Several measures are available for describing individually, or in combination, the severity of a LOS F condition:

- *Demand-to-capacity ratios* describe the extent to which demand exceeds capacity during the analysis period (e.g., by 1%, 15%).
- *Duration of LOS F* describes how long the condition persists (e.g., 15 min, 1 h, 3 h).
- *Spatial extent measures* describe the areas affected by LOS F conditions. They include measures such as the back of queue and the identification of the specific intersection approaches or system elements experiencing LOS F conditions.

Separate LOS Reporting by Mode and System Element

LOS is reported separately, by mode, for a given system element.

LOS is reported separately for each mode for a given system element. Each mode's travelers have different perspectives and could experience different conditions while traveling along a given roadway. Reporting LOS separately by mode also assists in assessing multimodal trade-offs when design options are evaluated. In contrast, use of a blended LOS risks overlooking quality of service deficiencies that discourage the use of nonautomobile modes, particularly if the blended LOS is weighted by the number of modal travelers. Other measures, such as person delay, can be used when an analysis requires a combined measure.

Identical values of some service measures (e.g., delay) can produce different LOS results, depending on the system element to which the service measure is applied. The Transportation Research Board (TRB) Committee on Highway Capacity and Quality of Service (HCQS Committee) believes that travelers' expectation of performance varies at different system elements but recognizes that further research is needed to understand fully the variation in traveler perceptions of LOS across facility types.

LOS as Part of a Bigger Picture

No single performance measure tells the full story of roadway performance.

Neither LOS nor any other single performance measure tells the full story of roadway performance. Depending on the particulars of a given analysis, queue lengths, demand-to-capacity ratios, average travel speeds, indicators of safety, quantities of persons and vehicles served, and other performance measures may be just as or even more important to consider, whether or not they are specifically called out in an agency standard. For this reason, the HCM provides methods for estimating a variety of useful roadway operations performance measures, not just methods for determining LOS. Chapter 7, Interpreting HCM with on a scale of "very good" to "very poor," or something similar. The qualitative ratings are later converted to numeric values for analysis purposes.

Some challenges to these types of studies include designing the instrument (e.g., field experiment, focus group) to capture all of the roadway, traffic, and control factors that might affect travelers' perceptions of operating conditions; excluding factors that may not be relevant but could distract study subjects; recruiting an adequate sample of study participants from both quantity and diversity perspectives; replicating desired conditions (for in-field experiments) for repeated observations; and accounting for the distribution of LOS responses that will result from each test scenario in the analysis methodology.

The advantage of this type of research approach is that, with application of an appropriate analysis methodology, multiple variables can be considered simultaneously, consistent with the high likelihood that travelers consider multiple factors when they evaluate operating conditions. Including multiple factors also gives agencies more options in seeking to achieve a desired LOS for a given mode or in balancing the needs of various modes.

Variables found to be statistically significant in predicting travelers' perceptions are incorporated into a mathematical function (hereinafter referred to as a *model*). In the model, the coefficients (i.e., weighting factors) associated with each of the variables are determined directly through a statistical analysis. The output from such a model is a value often referred to as a LOS score. The LOS score value generally represents the average score that travelers would give a facility or service. Furthermore, some of the HCM methodologies can directly estimate the threshold values between LOS letters, again, on the basis of traveler input. In determining the LOS letter, the LOS score value is compared with the statistically estimated threshold values.

Any number of factors can be included in this type of model, but for models to be useful from a practical perspective, only variables representing operational or design conditions are usually included. Operational conditions refer to variables such as delay and speed, while design conditions refer to variables such as median type and sidewalk presence. Traveler characteristics (e.g., age, gender, income) can affect LOS perceptions; however, these data are difficult to collect in a transportation engineering context. Thus, their utility in a LOS model is limited.

Several methodological approaches have been applied to relate traveler perceptions directly to LOS, including regression-based methods (*1–4*), ordered probit models (*5, 6*), and fuzzy clustering (*7*). These studies have addressed facilities such as urban and rural freeways, arterial streets, and signalized intersections. LOS methods resulting from some of these studies have been included in the HCM 2010, while others have been studied by the HCQS Committee to improve the understanding of techniques used in estimating traveler-based LOS.

The HCM's bicycle, pedestrian, and transit methods generally apply LOS measures based directly on traveler perceptions.

The HCM 2010 is the first HCM edition to incorporate LOS methodologies that are based directly on results from traveler perceptions of LOS. As research into traveler perception of LOS continues to mature and results from regional studies are validated nationally, the HCQS Committee expects to continue to include new LOS methodologies in future editions of the HCM. When research is not available to support traveler-perceived LOS methodologies, HCQS Committee–selected service measures and thresholds continue to be used.

DETERMINATION OF LOS F

The threshold between LOS E and LOS F is based on the judgment of the HCQS Committee in some instances and is determined directly from research on traveler perceptions of LOS in others. For example, in the case of basic freeway segments, the service measure and LOS thresholds were determined by the HCQS Committee; density was selected as the service measure and the LOS E–F density threshold value was selected as the density at which traffic flow transitions from undersaturated to oversaturated. In the case of bicycling on urban streets, the service measures were determined from research on traveler perception of LOS; the LOS E–F threshold was chosen as a value that represents the transition to a totally unacceptable condition (i.e., an average bicyclist will not ride under these conditions).

Thresholds between LOS A and E may be based on ranges of values that define particular operating conditions or may simply provide an even gradation of values from LOS A to E. As mentioned previously, in some studies on traveler perceptions of LOS, the methodological approach explicitly yields the model variables (e.g., speed, median presence) as well as the specific LOS thresholds. However, these thresholds are still a function of the total number of LOS categories originally included in the study.

A v/c ratio greater than 1.0 (capacity) is often used to define LOS F conditions.

The volume-to-capacity (v/c) ratio, or more correctly, demand-to-capacity (d/c) ratio, is a special-case service measure. It cannot easily be measured in the field, nor is it a measure of traveler perceptions. Until capacity is reached (i.e., when flow breaks down on uninterrupted-flow facilities and when queues build on interrupted- or uninterrupted-flow facilities), these ratios are not perceivable by travelers. Therefore, the HCM often uses a v/c (d/c) ratio of greater than 1.0 (i.e., capacity) as an additional test for defining when LOS F occurs but does not use these ratios to define other LOS ranges.

SERVICE MEASURES FOR SPECIFIC SYSTEM ELEMENTS

Crosscutting Issues

Motorized Vehicle Mode

LOS for the motorized vehicle mode reflects automobile driver perspectives, but not necessarily those of other motorized vehicle users.

A facility's capacity to serve the motorized vehicle mode reflects the effects of all motorized vehicles using the facility, including trucks, recreational vehicles, motorcycles, and intercity buses. In contrast, LOS for the motorized vehicle mode reflects the perspective of automobile drivers, but not necessarily the perspectives of other motorized vehicle users. Although automobiles are usually the dominant motorized vehicle type on roadways, analysts should use care in interpreting LOS results in special cases, such as intermodal terminal access routes, where trucks may dominate.

Pathways parallel to freeways and multilane highways are analyzed by using the off-street facility procedures.

Pedestrian and Bicycle Modes

Depending on local regulations, pedestrians and bicyclists may be allowed on all types of uninterrupted-flow facilities, including sections of freeways. However, research is only available to support LOS estimation methods for bicyclists traveling on two-lane and multilane highways. Pathways that are parallel to freeways and multilane highways use the service measures for off-street pedestrian and bicycle facilities. Of the various types of interrupted-flow system elements, pedestrian and bicycle service measures are provided for urban street facilities, urban street segments, signalized intersections, and off-street pedestrian and bicycle facilities. Pedestrian LOS can also be calculated for two-way STOP-controlled intersections and roundabouts.

Transit Mode

Bus service on uninterrupted-flow facilities typically serves longer-distance trips, with few (if any) stops. The *Transit Capacity and Quality of Service Manual* (TCQSM) (*8*) provides performance measures that can be used to evaluate bus service along uninterrupted-flow facilities as well as rail service operating within an uninterrupted-flow facility's right-of-way.

Transit service measures are provided only for transit service operating in mixed traffic or in exclusive lanes on urban streets. Consult the TCQSM for performance measures for other situations.

The HCM provides transit service measures for urban street facilities and segments to facilitate multimodal comparisons of urban street LOS. The TCQSM provides identical service measures for these system elements. The TCQSM provides additional performance measures for evaluating transit operations. Some of the HCM's performance measures, such as delay, may also be useful in multimodal comparisons—for example, in evaluating changes in person delay at an intersection as a result of a project being considered.

Freeway and Multilane Highway Service Measures

Motorized Vehicle Mode

Density is the motorized vehicle service measure for all freeway and multilane highway system elements.

Although travel speed is a major concern of drivers that relates to service quality, freedom to maneuver within the traffic stream and proximity to other vehicles are equally noticeable concerns. These qualities are related to the *density* of the traffic stream. Unlike speed, density increases as flow increases up to capacity, resulting in a service measure that is both perceivable by motorists and sensitive to a broad range of flows. Density is used as the service measure for freeway facilities, basic freeway segments, ramp junctions, weaving segments, and multilane highways.

Bicycle Mode

Bicycle LOS for multilane highways is based on a *bicycle LOS score* model. The model uses variables determined from research relating to bicyclists' comfort and perceived exposure while riding on multilane highways, such as separation from traffic, motorized traffic volumes and speeds, heavy-vehicle percentage, pavement quality, and (if present) on-highway parking.

Higher vehicle volumes, a greater proportion of trucks and buses, and higher vehicle speeds all act to decrease a bicyclist's perceived comfort and traffic exposure. Striped bicycle lanes or roadway shoulders add to the perceived sense of traffic separation and improve the LOS. Pavement quality affects bicyclists' ride comfort: the better the pavement quality, the better the LOS.

Two-Lane-Highway Service Measures

Motorized Vehicle Mode

Traveler expectations for and travel conditions on two-lane highways are different from those for other uninterrupted-flow facilities.

Traffic operations on two-lane, two-way highways differ from those on other uninterrupted-flow facilities. Lane changing and passing are possible only in the face of oncoming traffic. In any given direction, passing demand increases as flows increase. Passing capacity decreases as opposing flows increase. Therefore, on two-lane highways, unlike other types of uninterrupted-flow facilities, traffic flow in one direction influences flow in the other direction. Motorists must adjust their travel speeds as volume increases and the ability to pass declines.

Efficient mobility is the principal function of major two-lane highways that connect major traffic generators or that serve as primary links in state and national highway networks. These routes tend to serve long-distance commercial and recreational travelers, and long sections may pass through rural areas without traffic control interruptions. Consistent high-speed operations and infrequent passing delays are desirable for these facilities.

Other paved two-lane rural highways are intended to serve primarily an accessibility function. Although high speed is beneficial, it is not the principal concern. Delay—as indicated by the formation of platoons—is more relevant as a measure of service quality.

Two-lane roads also serve scenic and recreational areas where the vista and environment are meant to be experienced and enjoyed without traffic interruption or delay. A safe roadway is desired, but high-speed operation is neither expected nor desired. For these reasons, three service measures are used for two-lane highways: *percent time-spent-following, average travel speed,* and *percent of free-flow speed.*

Percent time-spent-following defined.

Percent time-spent-following reflects the freedom to maneuver. It is the average percentage of travel time that vehicles must travel in platoons behind slower vehicles because of the inability to pass.

Average travel speed defined.

Average travel speed reflects mobility on a two-lane highway: it is the length of a highway segment divided by the average travel time of all vehicles traversing the segment in a given direction during a designated interval.

Percent of free-flow speed defined.

Percent of free-flow speed reflects the ability of vehicles to travel at or near the posted speed limit.

LOS criteria use one or two of these measures. On major two-lane highways, for which efficient mobility is paramount, both percent time-spent-following and average travel speed define LOS. However, roadway alignments with reduced design speeds will limit the LOS that can be achieved. On highways for which accessibility is paramount and mobility less critical, LOS is defined only in terms of percent time-spent-following, without consideration of average travel speed. On two-lane highways in developed rural areas, LOS is defined in terms of percent of free-flow speed.

Bicycle Mode

Bicycle LOS for two-lane highways is determined by a *bicycle LOS score* model in the same manner as described above for multilane highways.

Urban Street Facility and Segment Service Measures

Motorized Vehicle Mode

The service measure for the motorized vehicle mode on an urban street is through-vehicle travel speed. Motorists traveling along arterial streets expect to be able to travel at or near the posted speed limit between intersections and to have to stop only infrequently. As delay due to traffic control devices and to other roadway users (e.g., vehicles stopped in a travel lane waiting to turn, buses stopping to serve passengers, or pedestrian crossings) increases, the lower the average speed and the lower the perceived LOS.

Chapter 18 presents an alternative performance measure well suited for determining multimodal LOS trade-offs and designing complete streets.

Research on automobile travelers' perceptions of LOS, as part of the National Cooperative Highway Research Program (NCHRP) 03-70 project, revealed that a combination of stops per mile and left-turn lane presence at signalized intersections had the highest statistical significance. However, the HCQS Committee elected to retain usage of a time-based service measure to analyze motorized vehicle LOS on urban streets for this edition of the HCM. The alternative NCHRP 03-70 methodology is also presented in Chapter 18, Urban Street Segments, since it is well suited for applications with a focus on determining multimodal LOS trade-offs and designing complete streets.

Pedestrian Mode

Urban street pedestrian LOS combines the quality of walking along a street, crossing at signalized intersections, and crossing the street between traffic signals.

Pedestrian LOS for urban streets is based on a *pedestrian LOS score* model that includes variables determined from research on pedestrians' perceptions of LOS. These variables relate to pedestrians' experiences walking along street links between signalized intersections, crossing side streets at signalized intersections, and crossing the street between signalized intersections.

The link component relates both to the density of pedestrians along the street and to pedestrian comfort and perceived exposure to traffic. The pedestrian density indicator is a function of pedestrian volumes and sidewalk width, while the nondensity indicator is a function of separation from traffic due to distance and physical objects, sidewalk presence and width, and motorized traffic volumes and speeds. The worse of the two indicators is used to determine pedestrian-perceived link LOS. The nondensity indicator more commonly determines LOS, but density can control in locations used by high volumes of pedestrians.

The signalized intersection component relates to pedestrian delay and perceived exposure to or interaction with traffic. The exposure elements of the indicator include potentially conflicting traffic volumes, parallel traffic volumes, parallel traffic speed, crossing width, and channelizing-island presence.

The roadway-crossing component is a function of the lesser of the delay in waiting for a gap to cross the street and the delay involved in diverting to the nearest signalized intersection. It also incorporates the link and signalized intersection components, which relate to the quality of the pedestrian environment experienced when pedestrians divert to a signal, either because of lower delay or a prohibition on crossings between signalized intersections.

Overall, pedestrian LOS is improved by the provision of sidewalks, wider sidewalks, a greater degree of separation from traffic, and reduced delays crossing the street at both signalized and unsignalized locations. Higher traffic volumes, higher traffic speeds, and wider streets tend to reduce pedestrian LOS.

Bicycle Mode

Urban street bicycle LOS combines the quality of bicycling along the street between traffic signals and the quality of passing through signalized intersections.

Bicycle LOS for urban streets is based on a *bicycle LOS score* model that includes variables determined from research on bicycle riders' perceptions of LOS. These variables relate to bicyclists' experiences at signalized intersections and their experiences on street links between signalized intersections. The intersection component relates to bicyclist comfort and perceived exposure to traffic and is a function of separation from traffic, cross-street width, and motorized traffic volumes. The link component similarly relates to comfort and perceived exposure. It is a function of separation from traffic, motorized traffic volumes, traffic speeds, heavy-vehicle percentage, presence of parking, pavement quality, and the frequency of unsignalized intersections and driveways between traffic signals.

Higher vehicle volumes, a greater proportion of trucks and buses, higher vehicle speeds, and presence of parking all decrease a bicyclist's perceived comfort. Striped bicycle lanes or roadway shoulders add to the perceived sense of traffic separation and improve the LOS. Pavement quality affects bicyclists' ride comfort: the better the pavement quality, the better the LOS.

Transit Mode

The transit service measure applies to bus, streetcar, and at-grade light rail services that make stops along an urban street.

The service measure combines traveler perceptions of walking to a transit stop, waiting for a transit vehicle, and riding on the vehicle.

Transit LOS for urban streets is based on a *transit LOS score* model that includes variables determined from research on transit riders' perceptions of LOS. The variables relate to passengers' experiences walking to a transit stop on the street, waiting for the transit vehicle, and riding on the transit vehicle. The walking-to-the-stop component is based on the street's pedestrian LOS score: transit passengers are usually pedestrians before and after their transit trip—and improvements to the pedestrian environment along streets with transit service contribute to a better LOS. The waiting component is a function of the transit vehicle frequency (relating to wait time and trip-making convenience), service reliability (unplanned passenger waiting time at the stop), and the presence of shelters and benches (which make waiting time more comfortable). Finally, the riding-on-the-vehicle satisfaction is a function of average travel speed (a convenience factor) and passenger loads (a comfort factor).

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CHAPTER 6
HCM AND ALTERNATIVE ANALYSIS TOOLS

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

OVERVIEW

The analysis tools provided by the *Highway Capacity Manual* (HCM) are part of a continuum of tools providing different levels of data needs, sensitivity to input factors, geographic and temporal scope, and detail of outputs. The HCM's tools can be categorized into three broad areas:

- *Operations-level tools.* These are the primary methodologies presented in the HCM's Volume 2 and 3 chapters. They are sensitive to a variety of input factors and have a correspondingly high level of data needs that must be supplied by the analyst on the basis of field or forecast data (or a combination). HCM methods are *deterministic* (i.e., each model run produces the same results, given the same inputs), *macroscopic* (i.e., evaluate the traffic stream as a whole rather than individual vehicles), and generally work with 15-min analysis periods as the smallest unit of time.
- *Application of defaults to operations-level tools.* In many cases, supplying a field-measured or forecast value for every HCM model input may be impractical or unnecessary. Default values can be judiciously substituted for unknown input values when HCM operations methods are applied. The use of local default values is preferred—and a method for developing them is suggested in Appendix A of this chapter—but the HCM also suggests default values when local values are not available.
- *Planning-level tools.* These include (*a*) the application of operations methods with all inputs defaulted that are allowed to be defaulted, (*b*) service volume tables that provide maximum daily or hourly volumes for a particular level of service (LOS) given a set of assumed conditions, and (*c*) other tools that approximate an HCM operations method but require fewer inputs and fewer calculation steps. These tools are typically applied as screening tools; as means for obtaining quick, approximate answers; and as easy-to-use methods for providing inputs to other analysis tools.

Alternative tools are defined as all analysis procedures outside the HCM that may be used to compute measures of transportation system performance for analysis and decision support. The HCM and alternative tools may be used during different stages of a planning or project development process, depending on the analysis needs (e.g., available data, desired level of detail) at a given time.

Alternative tools span the range from very simple (e.g., single equations estimating a single performance measure) to highly complex (e.g., travel demand models covering an entire region's transportation system). Analysts might consider alternative tools for a variety of reasons, including the following, among others: conditions outside the range covered by an HCM methodology, analyses requiring performance measures not produced by the HCM, and analyses in which the quantity of data required to calculate a performance measure (e.g., areawide multimodal networks) makes HCM methods impractical.

One exception to the statement that HCM methods are deterministic is the travel time reliability method, which uses a random number seed to generate scenarios. However, given the same seed, the model will produce the same travel time distribution.

CHAPTER ORGANIZATION

Section 2 describes the three main types of analysis tools provided by the HCM: (*a*) generalized service volume tables, (*b*) application of HCM operations methods with default values, and (*c*) application of HCM operations methods with measured or forecast values. Typical applications for each of these types of tools are described.

Section 3 introduces the range of alternative tools, describes traffic modeling terminology and concepts, examines the conceptual differences between the HCM's analytical modeling and simulation modeling, and presents situations in which alternative tools might supplement HCM procedures. The section provides modeling frameworks for applying alternative tools to different transportation system elements and compares the principal performance measures available from the HCM and from alternative tools. Finally, it provides guidance on the selection of analytical tools for a given situation, along with general guidance on using simulation-based traffic analysis tools for capacity and performance analysis.

Two appendices to the chapter will be of particular interest to analysts conducting planning and preliminary engineering analyses. Appendix A provides guidance on developing local default values, and Appendix B describes how to develop local generalized service volume tables.

RELATED HCM CONTENT

Other HCM content related to this chapter is the following:

- Chapter 7, Interpreting HCM and Alternative Tool Results, where Section 3 includes guidance on defining, measuring, and comparing key outputs of alternative tools when such outputs are intended to be used with or compared with those of the HCM;
- Chapter 36, Concepts: Supplemental, where Section 5 provides guidance on using vehicle trajectory analysis as the "lowest common denominator" for comparing performance measures from different analysis tools;
- The Scope subsections within the Methodology sections of all Volume 2 and 3 chapters, which provide specific guidance about when alternative tools might be considered for analyzing a particular system element;
- The Use of Alternative Tools subsections within the Applications sections of all Volume 2 and 3 chapters, which provide specific guidance on applying alternative tools to the analysis of a system element;
- Case Study 4, Alternate Route 7, in the *HCM Applications Guide* in Volume 4, which provides a high-level example of applying a simulation tool to a freeway facility analysis;
- Case Study 6, I-465 Corridor, Indianapolis, in the *HCM Applications Guide* in Volume 4, which demonstrates how a network simulation model can be used to augment studies conducted with HCM methodologies; and
- The *Planning and Preliminary Engineering Applications Guide to the HCM* in Volume 4, which provides guidance and case study examples of using the HCM in a variety of planning applications.

2. HCM-BASED TOOLS

The HCM provides three main types of tools for analyzing roadway operations: (*a*) generalized service volume tables, (*b*) methods relying on the extensive use of default values, and (*c*) operations-level analysis where all or nearly all inputs come from measured or forecast values. Different HCM tools may be used at different points in the same analysis or at different times as a project progresses from planning to preliminary engineering to design. HCM tools may also be combined with non-HCM (*alternative*) tools in a similar manner. This section describes the potential use of HCM-based tools; the next section does the same for alternative tools.

GENERALIZED SERVICE VOLUME TABLES

Service volume tables provide estimates of the maximum number of vehicles a system element can carry at a particular LOS, given a set of assumed conditions.

A service volume table provides an analyst with an estimate of the maximum number of vehicles that a system element can carry at a given LOS. The use of a service volume table is most appropriate in certain planning applications when evaluation of every segment or node within a study area is not feasible. Examples are city, county, or statewide planning studies in which the size of the study area makes a capacity or LOS analysis for every system element infeasible. For these types of applications, the focus of the effort is on highlighting potential problem areas (for example, locations where demand may exceed capacity or where a desired LOS threshold may be exceeded). For such applications, a service volume table can be a useful sketch-planning tool, provided the analyst understands the limitations of this method. Once potential problem areas have been identified, other tools (HCM-based or alternative) can be used to perform more detailed analyses for locations of interest.

A service volume represents the maximum number of vehicles that the system element can carry at a specified LOS, given assumed inputs.

As described in more detail in Appendix B, generalized service volume tables are developed by holding constant all input values to a particular HCM methodology—except demand volume. Demand volume is increased until the service measure for the methodology reaches the threshold for a given LOS (e.g., the threshold between LOS B and C). That demand volume then becomes the *service volume* for the given LOS (in the example above, for LOS B). The service volume represents the maximum number of vehicles that the system element can carry at the given LOS, given the assumed inputs.

Service volume results should be applied with care, since actual conditions will likely vary in some way from the assumptions used to develop the table.

The characteristics of any given roadway will likely vary in some way from the assumed input values used to develop a service volume table. Therefore, the results from a service volume table should be treated as rough approximations. These tables should not be used as a substitute for other tools in making a final determination of the operational adequacy of a particular roadway. Application of local service volume tables based on local default values, as described in Appendices A and B, helps make the results less approximate than would application of the HCM's tables, which are based on national default values.

For ease of use, generalized service volume tables require a minimum of user inputs—typically, key design parameters that have the greatest influence on a facility's capacity and LOS, such as the number of lanes. With these inputs, a user can read the service volume for a given LOS directly from the table and compare

- An *algorithm* is, by dictionary definition (2), "a set of rules for solving a problem in a finite number of steps." This definition suits the HCM's purposes.
- A *model* is, by dictionary definition (2), "a hypothetical description of a complex entity or process." Here is the root of the inconsistent usage. On the basis of this definition the word can be, and has been, applied to many different objects. A more focused definition is required. One definition in common use is that a model is "a representation of a system that allows for investigation of the properties of the system and, in some cases, prediction of future outcomes"(3). For HCM purposes, *model* is used in this sense but is more precisely defined as "a procedure that uses one or more algorithms to produce a set of numerical outputs describing the operation of a transportation segment or system, given a set of numerical inputs." By this definition, each of the performance analysis procedures specified in Volumes 2 and 3 constitutes a model. This term is generally used with an adjective to denote its purpose (e.g., delay model).
- A *computational engine* is the software implementation of one or more models that produces specific outputs given a set of input data.
- A *traffic analysis tool,* often shortened in the HCM to *tool,* is a software product that includes, at a minimum, a computational engine and a user interface. The purpose of the user interface is to facilitate the entry of input data and the interpretation of results.
- A *model application,* sometimes referred to as a *scenario,* specifies the physical configuration and operational conditions to which a traffic analysis tool is applied.

Inconsistency in terminology arises because each of these five objects has been characterized as a model in the literature, since each one satisfies the dictionary definition. The distinction between the five terms is made here in the hope of promoting more consistent usage.

Additional Modeling Definitions

Another set of terminology that requires more precise definitions deals with the process by which the analyst ensures that the modeling results provide a realistic representation of the situation being analyzed. The following terms are defined in Volume III of the *Traffic Analysis Toolbox* (4):

- *Verification:* The process by which the software developer and other researchers check the accuracy of the software implementation of traffic operations theory. The extent to which a given tool has been verified is listed as an important tool selection criterion in this chapter.
- *Calibration:* The process by which the analyst selects the model parameters that result in the best reproduction of field-measured local traffic conditions by the model.
- *Validation:* The process by which the analyst checks the overall model-predicted traffic performance for a street–road system against field measurements of traffic performance, such as traffic volumes, travel

times, average speeds, and average delays. Model validation is performed on the basis of field data not used in the calibration process.

Traffic Analysis Tool and Model Categories

Different types of tools have different objectives and provide different types of output.

Volume I of the *Traffic Analysis Toolbox* identifies the following categories of traffic analysis models (*1*):

- *Sketch-planning tools* produce general order-of-magnitude estimates of travel demand and transportation system performance under various transportation system alternatives.
- *Travel demand models* forecast long-term travel demand on the basis of current conditions and projections of socioeconomic characteristics and changes in transportation system design.
- *HCM-based analytical deterministic tools* predict capacity, density, speed, delay, and queuing on a variety of transportation facilities.
- *Traffic signal optimization tools* are primarily designed to develop optimal signal phasing and timing plans for isolated signalized intersections, arterial streets, or signal networks.
- *Macroscopic simulation models* are based on the deterministic relationships of the flow, speed, and density of the traffic stream.
- *Microscopic simulation models* simulate the movement of individual vehicles on the basis of car-following and lane-changing theories.
- *Mesoscopic models* combine the properties of microscopic and macroscopic simulation models.
- *Hybrid models* utilize microscopic and mesoscopic models simultaneously. These tools are intended to be applied to very large networks containing critical subnetworks connected by several miles of essentially rural facilities. Microscopic modeling is applied to the critical subnetworks, while the connecting facilities are modeled at the mesoscopic or macroscopic level. Regional evacuation models are a typical example of hybrid model application.

Stochastic and Deterministic Models

The HCM's methodologies are deterministic—given the same set of inputs, the methods will produce the same result each time.

Most simulation models are stochastic—given identical inputs but a different random number seed, model runs will produce different results.

A *deterministic* model is not subject to randomness. Each model run will produce the same outcome. If these statements are not true and some attribute of the model is not known with certainty, the model is *stochastic*. Random variables will be used to represent those attributes of the model not known with certainty. Descriptions of how these random numbers are selected to obtain sample values of the parameter of interest (i.e., from its cumulative distribution function) can be found in various texts (e.g., *5–8*). Different random number sequences will produce different model results; therefore, the outcome from a simulation tool based on a stochastic model cannot be predicted with certainty before analysis begins. Stochastic models aid the user in incorporating variability and uncertainty into the analysis.

Static Flow and Time-Varying Flow Models

The terms *static flow* and *time-varying flow* relate to the temporal characteristics of the traffic flows in the simulation model. The terms differentiate between a model that uses constant traffic flow rates from one time period to another and a model that does not. This differentiation is not to be confused with whether the model can represent internally time-varying flows that occur because of simulated events (e.g., incidents, signal cycling, ramp metering, high-occupancy-vehicle lane closures). The difference is in the type of input flows that can be specified.

In static flow models, users provide a single set of flow rates. The model may vary headways, but the demand is fixed and does not change throughout the duration of the analysis.

In the static flow case, traffic flows are provided just once, as a set of constants. A tool may vary the individual headways stochastically, but the flow rates are fixed. Put another way, the demand is fixed and does not change throughout the duration of the analysis.

Time-varying models allow flow rates to change with time. Users supply more than one set of flow rates so that the demand can vary over time. Most models change flows once an hour, but some allow more frequent changes.

In the time-varying case, flow rates can change with time. More than one set of flow rates must be specified so that the demand can vary over time. The flexibility of specifying more than one set of flow rates is particularly useful when major surges in traffic need to be examined, such as the ending of a special event or peak periods when a pronounced variation in traffic flows exists.

Descriptive and Normative Models

Descriptive models show how events unfold given a logic that describes how the objects involved will behave.

Normative models try to identify a set of parameters that provide the best system performance.

The terms *descriptive* and *normative* refer to the objective of performing the analysis with simulation models. If the objective of the model is to describe how traffic will behave in a given situation, the model is most likely to be descriptive. It will not try to identify a given set of parameters that provide the best system performance but rather will show how events will unfold given a logic that describes how the objects involved will behave. For example, a simulation model could predict how drivers will behave in response to traffic flow conditions. A model attempting to shape that behavior through advance lane blockage signs would not necessarily be a descriptive model.

If the model has an objective and seeks to optimize that objective, it is a normative model. Conversely, if it has an objective but does not seek to optimize that objective by changing the design or operational parameters (e.g., signal timing), it is a descriptive model.

Normative models try to identify a set of parameters providing the best system performance. An external influence (most often referred to as an objective function) tries to force the system to behave in some optimal way. A good example is a model that tries to optimize signal timings. Another illustration is a freeway network model that requires drivers to alter their path choices to optimize some measure of system performance. In both cases, the behavior of the system is modified through an external influence, probably on an iterative basis, to create a sequence of realizations in which the objective function value is improved, as in minimizing total travel time or total system delay.

DTA models are a type of descriptive model using an objective (minimize the travel time or disutility associated with a trip) that is gradually improved over a sequence of iterations until the network reaches a state of equilibrium.

Traffic assignment models are a special case, because they use an objective that is gradually improved over a sequence of iterations. In this case, the objective is for each driver to minimize either the travel time for the trip or some other quantitative measure of the general cost or disutility associated with the trip. Traffic assignment models are characterized as either *static* or *dynamic,* depending on whether the demand characteristics are constant or time-varying. Most simulation tools have some form of dynamic traffic assignment (DTA). Because of its computer resource demands, DTA is often implemented at the mesoscopic level. DTA models are often combined with microsimulation models to create hybrid models.

The optimization process may be characterized as either *system-optimal* or *user-optimal*. A user-optimal solution does not necessarily produce an optimal result for the system as a whole and vice versa. With user-optimal models, the objective being applied reflects a behavioral assumption, and therefore the model is primarily descriptive. System-optimal models enforce some changes in driver behavior and are therefore normative. The formulation of the generalized cost (disutility) function can be expanded to reflect actual driving behavior more accurately—for example, by taking into account travel time reliability, toll prices, number of stops, and the driver's familiarity with typical traffic conditions.

The important point is that the analyst needs to know which type of model is being used and how that type influences the model's predictions. For example, assume that the analyst is dealing with a scenario in which the signal timing is fixed and drivers can alter their path choices in response to those signal timings (in a way that replicates how they would actually behave). This is a descriptive model and is a common application of a DTA model as mentioned above. Even though the analyst can change the signal timings and see how the drivers respond (and how the system performance changes), the model is still describing how the system would behave for a given set of conditions. On the other hand, if the analyst alters the scenario so that it seeks a better set of signal timings, a normative model has been created.

A descriptive model is implied if the analyst introduces a new demand–supply paradigm, such as congestion pricing, based on a field study. A new demand-side routine could be developed to predict how drivers alter path choices in response to congestion prices, and a supply-side routine could be developed that seeks to set those prices in some responsive and responsible way in an effort to produce a desirable flow pattern. Even though two competing optimization schemes are at work, each describes how a portion of the system is behaving in response to inputs received. There is no explicit intent to optimize the system performance in a specific manner.

CONCEPTUAL DIFFERENCES BETWEEN ANALYTICAL AND SIMULATION TOOLS

There are some conceptual differences between the HCM's analytical modeling and simulation modeling. It is useful to examine these differences before addressing alternative tool applications. One important difference is that HCM procedures work with fixed demand, typically the output of assignment (planning or dynamic). Most of the other differences may be described in terms of how analytical and simulation tools deal with various traffic flow phenomena. Examples of the significant differences are identified in general terms in Exhibit 6-1.

Exhibit 6-1
Comparison of Methods for Addressing Traffic Phenomena by the HCM and Typical Microsimulation Tools

Traffic Phenomenon	Deterministic HCM Treatment	Typical Microsimulation Treatment
Right turn on red	Subtract right-turn-on-red volume from demand	Microscopic model of gap acceptance and follow-up time
Permitted left turns	Empirical model of capacity versus opposing volume, with minimum capacity determined by an assumption of two sneakers per cycle	Microscopic model of gap acceptance and follow-up time
STOP sign entry	Macroscopic model of gap acceptance and follow-up time	Microscopic model of gap acceptance and follow-up time
Channelized right turns	Subtract right-turning volume from demand	Microscopic model of gap acceptance and follow-up time; implicit effects of right-turn queues
Ramp merging	Empirical model of merge capacity versus freeway volume in the two outside lanes	Microscopic model of gap acceptance and follow-up time (some tools incorporate cooperative merging features)
Merging during congested conditions	Not addressed	Microscopic model of gap acceptance
Lane-changing behavior	Macroscopic model based on demand volumes and geometrics	Microscopic model of lane-changing behavior
Queue start-up on green	Fixed start-up lost time subtracted from the displayed green time	Stochastic lost time applied to the first few vehicles in the departing queue
Response to change interval	Fixed extension of green time added to the displayed green time	Kinematic model of stopping probability
Actuated signal operation	Deterministic model for computing green times as a function of demand and operating parameters	Embedded logic emulates traffic-actuated control explicitly; tools vary in the level of emulation detail
Delay accumulation	Analytical formulation for uniform delay based on the assumption of uniform arrivals over the cycle and uniform departures over the effective green	These three effects are combined implicitly in the accumulation and discharge of individual vehicles over the analysis period
Progression quality	Adjustment factor applied to the uniform delay term	
Random arrivals	Analytical formulation for incremental delay	
Generation of vehicles	Incremental delay formulation assumes Poisson arrivals (mean = variance) at the stop line; the variance–mean ratio is reduced for traffic-actuated control as a function of the unit extension	Individual vehicles are introduced into entry links randomly, on the basis of a specified distribution
Effect of oversaturation	A third analytical formulation, d_3, is introduced to cover the additional delay due to an initial queue	Oversaturated operation and residual queues are accounted for implicitly in the accumulation and discharge of individual vehicles
Residual queue at the end of analysis period	Analytical formulation computes the residual queue when $d/c > 1.0$; the residual queue from one period becomes the initial queue for the next period	

APPROPRIATE USE OF ALTERNATIVE TOOLS

Situations in which alternative tools might supplement HCM procedures.

Use of alternative tools to supplement HCM capacity and quality-of-service procedures should be considered when one or more of these conditions apply:

- The configuration of the facility or range of the analysis has elements that are beyond the scope of the HCM procedures. Each Volume 2 and 3 chapter identifies the specific limitations of its own methodology.
- Viable alternatives being considered in the study require the application of an alternative tool to make a more informed decision.
- The measures produced by alternative tools are compatible with corresponding HCM measures and are arguably more credible than the HCM measures.
- The measures are compatible with corresponding HCM measures and are a by-product of another task, such as vehicle delays produced by optimization of a network traffic control system.
- The measures are compatible with corresponding HCM measures and the decision process requires additional performance measures, such as fuel consumption and emissions, that are beyond the scope of the HCM.
- The system under study involves a group of different facilities or travel modes with mutual interactions involving several HCM chapters. Alternative tools are able to analyze these facilities as a single system.
- Routing is an essential part of the problem being addressed.
- The quantity of input or output data required presents an intractable problem for the HCM procedures.
- The HCM procedures predict oversaturated conditions that last throughout a substantial part of a peak period or queues that overflow the available storage space, or both.
- Active traffic and demand management (ATDM) or other advanced strategies are being evaluated.

Compatibility of performance measures with the HCM procedures is essential for the use of alternative tools to supplement or replace the HCM procedures.

In addition, when a specific HCM procedure has been developed by using simulation results as a surrogate for field data collection, direct use of the underlying simulation tool to deal with complex configurations that are not covered in the HCM might be appropriate.

The following are considerations in the decision to use an alternative tool:

- Is use of the tool acceptable to the agency responsible for approving decisions that result from it?
- Are the necessary resources, time, and expertise available to apply the tool?
- Does the application rely on a traceable and reproducible methodology?
- Have assumptions used to apply the tool been sufficiently documented?
- Are sufficient and appropriate data available to capitalize on or leverage the strength of the tool?
- Is sufficient time available for calibration to promote a robust reliance on the model output?

Tools available for modeling freeways include HCM planning procedures, operational tools, and simulation tools.

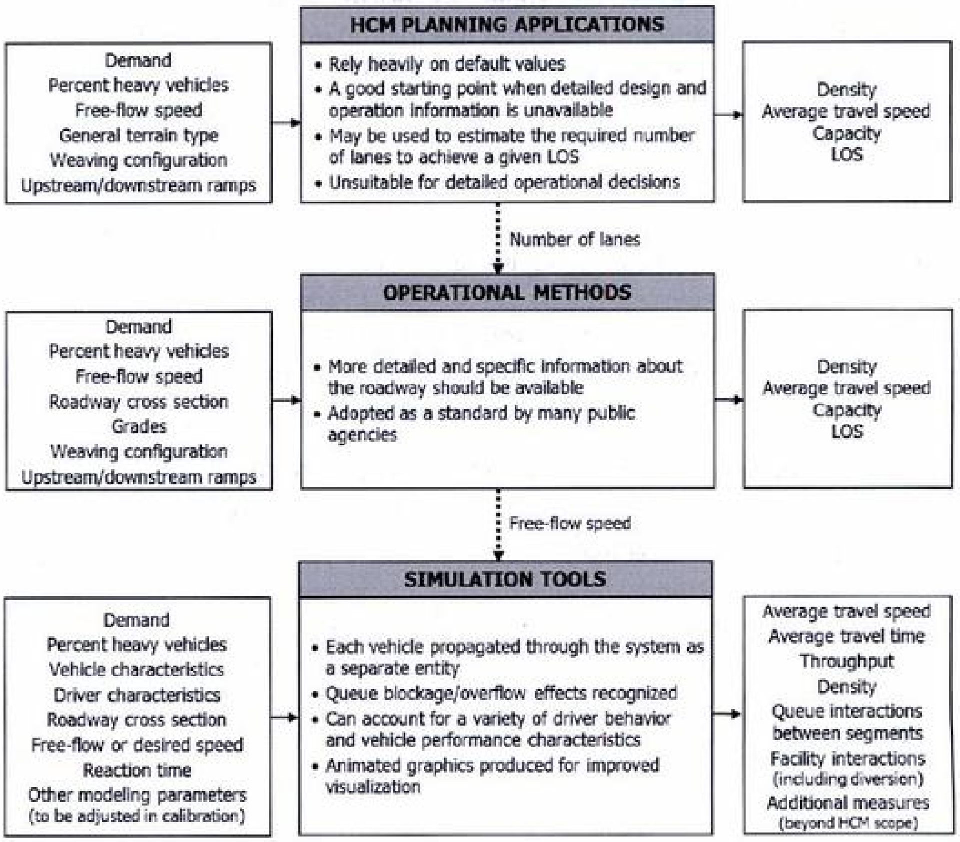
The principal classes of tools are

- HCM planning applications;
- Operational tools, including the HCM methodology described in Volume 2 and a variety of other macroscopic analysis tools; and
- Simulation tools that utilize microscopic, mesoscopic, and hybrid models.

Alternative tools find a much stronger application to freeway facilities than to individual freeway segments.

Most HCM freeway analysis limitations are apparent when a freeway is analyzed as a facility consisting of multiple segments of different types (e.g., basic, merge, weaving) by using the procedures given in Chapter 10, Freeway Facility Core Methodology. Alternative tools, especially microsimulation tools, find a much stronger application to freeway facilities than to individual segments.

Exhibit 6-3
Freeway Modeling Framework for the HCM and Alternative Tools



Urban Streets

Tools available for modeling urban streets include the HCM quick-estimation method for signalized intersections, HCM operational methods, arterial and network signal-timing tools, and microscopic simulation.

The modeling framework for urban streets, including their intersections, is presented in Exhibit 6-4. Each of the tools and procedures can be used in a stand-alone fashion; the potential flow of information between them indicates how they might fit into an overall analysis structure. The principal classes of tools are

- *HCM quick-estimation method for signalized intersections,* which is based primarily on critical movement analysis and default values;
- *HCM operational methods for urban streets,* including all types of intersections, which require more detailed traffic inputs and operating parameters;

- *Arterial and network signal-timing tools,* which produce recommended signal-timing plans based on measures that are generally similar to those produced by the HCM procedures; and
- *Microscopic simulation tools,* as described previously in this chapter.

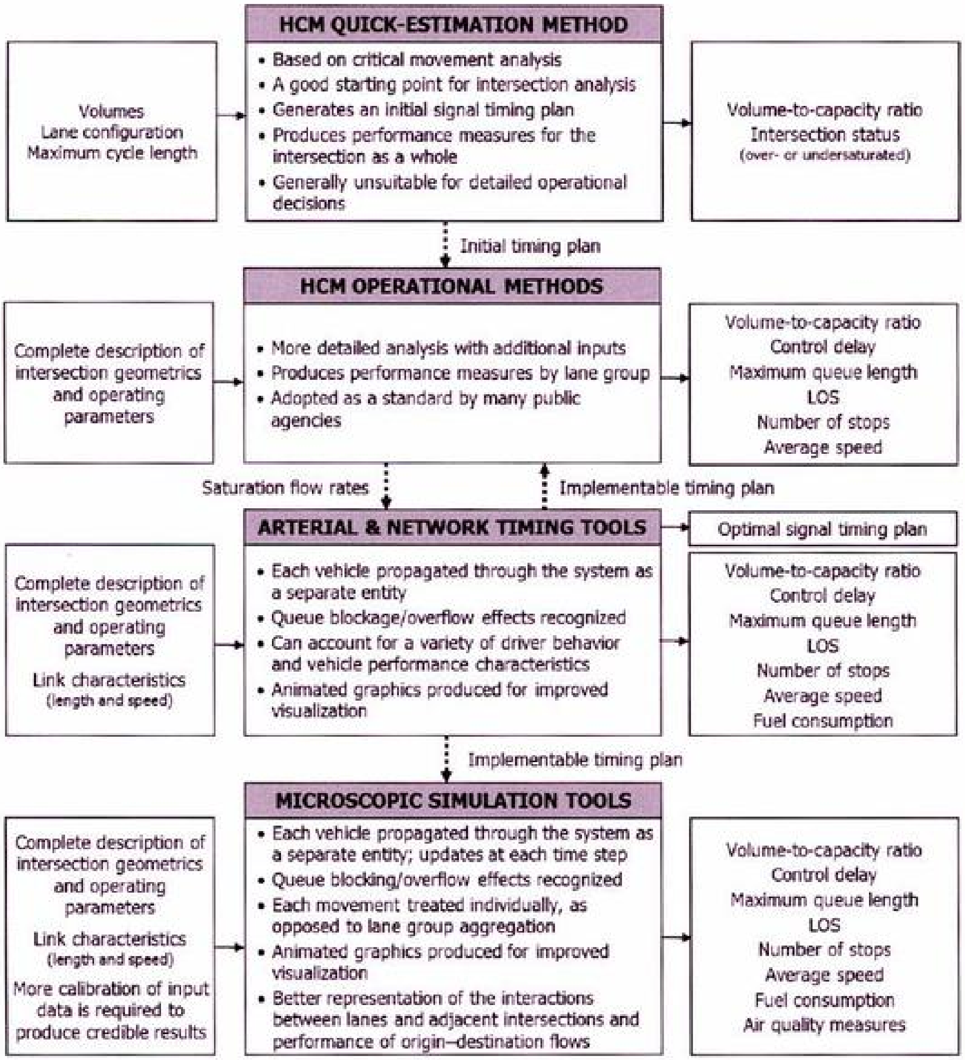
Signal-timing tools are mostly based on macroscopic analytical models of traffic flow. Because they are the only class of urban street analysis tool that generates a signal-timing plan design, they are frequently used as an alternative tool for this purpose. The signal-timing plan may be fed into the HCM operational analysis or used as input to a microsimulation tool.

Signal-timing tools generate signal-timing plans that can be used as inputs to HCM operational methods or to microsimulation tools.

Microsimulation tools are used in urban street analysis, mainly to deal with complex intersection phenomena beyond the capabilities of the HCM. These tools evaluate interactions between arterial segments, including the effect of various types of unsignalized intersections. They are also applied in evaluating networks and corridors with parallel facilities with the use of DTA routines.

Microsimulation tools are used to deal with complex intersection interactions beyond the capabilities of the HCM.

Exhibit 6-4
Urban Street Modeling Framework for the HCM and Alternative Tools



Source: *Signalized Intersections: Informational Guide* (*9*).

Two-Lane and Multilane Highways

At the time of writing, the HCM was the only deterministic tool in common use for two-lane and multilane highways.

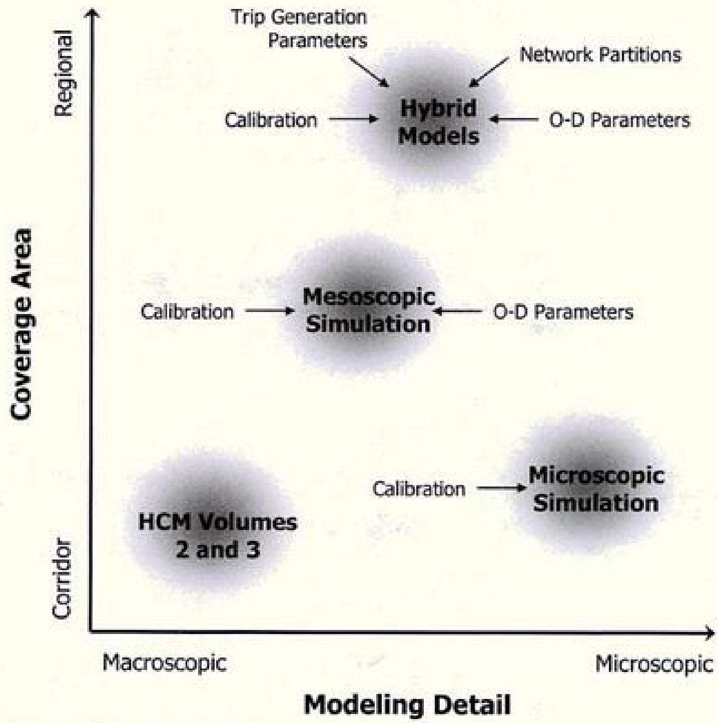
At this point, application of alternative tools for the analysis of either type of highway is minimal. The HCM is the only macroscopic deterministic tool in common use, although some states such as Florida have developed their own analysis tools that implement derivatives of HCM procedures (*10*). At the time of writing, microsimulation models were in various stages of development. Some two-lane highway simulation tools were beginning to emerge, but there was insufficient experience to provide guidance for their use as an alternative to the methodology provided here.

Corridor and Areawide Analysis

Corridor and areawide analysis is probably the most important application for alternative tools.

Corridor and areawide analysis is an important application for alternative tools. The HCM procedures deal mainly with points and segments and are limited in their ability to recognize the interaction between segments and facilities. The overall modeling framework for corridor and areawide analysis is presented in Exhibit 6-5, which shows the relationship of the HCM to the broad field of corridor and areawide analysis models.

Exhibit 6-5
Corridor and Areawide Analysis Modeling Framework for the HCM and Alternative Tools



Note: O-D = origin–destination.

An excellent reference for corridor and areawide simulation (*11*) is available from a U.S. Department of Transportation research initiative on integrated corridor modeling. It provides detailed guidance on conducting large-scale simulation projects. This section presents an overview of corridor and areawide simulation from the perspective of HCM users, but considerably more detailed information is presented in the report (*11*), including a more detailed analysis framework.

The framework for corridor and areawide analysis differs from the framework presented for freeways and urban streets in three ways:

1. The HCM procedures account for a much smaller part of the modeling framework.
2. Different levels of simulation modeling are represented here. Simulation of urban streets and freeways is typically performed only at the microscopic level.
3. The framework is two-dimensional, with the coverage area as one dimension and the modeling detail as the other.

The model classes shown in Exhibit 6-5 depict the trade-off between these characteristics. The trade-off between coverage area and modeling detail is evident:

The selection of a model class (microscopic, mesoscopic, or hybrid) reflects a trade-off between coverage area and modeling detail.

- *Microscopic simulation* provides more detail and more coverage than the HCM procedures. The additional detail comes from the microscopic nature of the model structure. The additional coverage comes from the ability to accommodate multiple links and nodes.
- *Mesoscopic simulation* provides more coverage with less modeling detail than microscopic simulation. In addition to accommodating larger areas, mesoscopic models are computationally faster than microscopic models and are thus well suited to the iterative simulations required for DTA, which can be time-consuming.
- *Hybrid modeling* uses network partitioning to treat more critical parts of the system microscopically and less critical parts mesoscopically—or even macroscopically. In this way, the regional coverage may be expanded without losing essential detail. A typical application for hybrid modeling might be interurban evacuation analysis, which must accommodate a large geographical area without loss of detail at critical intersections and interchanges.

PERFORMANCE MEASURES FROM ALTERNATIVE TOOLS

The tool selected for a given analysis needs to provide performance measures that realistically reflect the attributes of the problem being studied.

Before the analyst can select the appropriate tool, the performance measures that realistically reflect attributes of the problem under study must be identified. For example, when oversaturated conditions are studied, use of a tool that quantifies the effects of queuing as well as stops and delay is necessary. If the methodologies presented in Volumes 2 and 3 do not provide a particular performance measure of interest to the analyst (e.g., fuel consumption and emissions), an alternative tool might be required. Exhibit 6-6 provides a summary of important performance measures for the procedures discussed in Volumes 2 and 3. The applicability of the HCM procedures and alternative tools is indicated for each chapter in this exhibit.

When an alternative tool is used to analyze highway capacity and quality of service, its performance measures should ideally be compatible with those prescribed by the HCM. Chapter 7 provides general guidance on this topic, while selected chapters in Volumes 2 and 3 provide specific guidance for certain system elements.

If an alternative tool is used to analyze highway capacity and quality of service, the performance measures generated by the tool should, to the extent possible, be compatible with those prescribed by the HCM. Alternative tools frequently apply the same terminology to performance measures as the HCM, but divergent results are often obtained from different tools because of differences in definitions and computational methods. General guidance on reconciling performance measures is given in Chapter 7, Interpreting HCM and Alternative Tool Results. More specific guidance on dealing with performance measures from alternative tools is given in several of the procedural chapters in Volumes 2 and 3.

Exhibit 6-6
Principal Performance Measures from the HCM and Alternative Tools

Uninterrupted-Flow Chapters (Volume 2)									
HCM Chapter and Topic	**Speed**	**Delay**	**Through-put**	**Reli-ability**	**Density**	**% Time-Spent-Following**	**Passing**	**Environ-mental**	**Demand/ Capacity**
10. Freeway Facilities	H, A	H, A	H, A	X	H, A	X	X	A	X
11. Freeway Reliability	H, A	X	X	H, A	X	X	X	X	X
12. Basic Segments	H, A	A	H, A	X	H, A	X	X	A	H
13. Weaving	H, A	A	H, A	X	H, A	X	X	A	H
14. Merges/Diverges	H, A	A	H, A	X	H, A	X	X	A	H
15. Two-Lane Highways	H, A	H	H	A	A	H	H, A	A	H

Interrupted-Flow Chapters (Volume 3)									
HCM Chapter and Topic	**Delay**	**Stops**	**Through-put**	**Reli-ability**	**Queue Length**	**Cycle Failure**	**Environ-mental**	**Speed**	**Demand/ Capacity**
16. Urban St. Facilities	H, A	H, A	H, A	X	H, A	A	A	H, A	H
17. Urban St. Reliability	X	X	X	H, A	X	X	X	H, A	X
18. Urban St. Segments	H, A	H, A	H, A	X	H, A	A	A	H, A	H
19. Signals	H, A	A	H, A	X	H, A	A	A	X	H
20. TWSC	H, A	A	H, A	X	H, A	X	A	A	H
21. AWSC	H, A	A	H, A	X	H, A	X	A	A	H
22. Roundabouts	H, A	A	H, A	X	H, A	X	A	A	H
23. Ramp Terminals	H, A	A	H, A	X	H, A	A	A	X	H
24. Pedestrian/Bicycle	X	X	X	X	X	X	X	H	H[a]

Source: Adapted from Dowling (*12*).
Notes: [a] Pedestrian mode only.
H = Performance measures computed by the HCM and some deterministic tools with similar computational structures.
A = Performance measures computed by alternative tools (mostly simulation-based).
X = Performance measures do not apply to this chapter.
St. = Street, TWSC = Two-way STOP-control, AWSC = All-way STOP-control.

TRAFFIC ANALYSIS TOOL SELECTION CRITERIA

The Traffic Analysis Toolbox *is available at http://ops.fhwa.dot.gov/trafficanalysistools/.*

The success of a traffic analysis project depends on the selection of the best tool or tools for the purpose, followed by the proper application of the selected tools. Both of these issues are addressed in detail in the *Traffic Analysis Toolbox*, and the guidance provided in the *Toolbox* [e.g., in Volume II (*13*)] should be studied thoroughly before a major traffic analysis project is undertaken.

Determining Project Scope

Questions to ask during the scoping of a traffic analysis project.

A properly defined problem and project scope are prerequisites to the correct selection of tools or procedures for the project. Answers to the following questions will assist in scoping the project:

1. What is the operational performance problem or goal of the study?
2. Does the network being studied include urban streets, freeways, rural highways, or any combination of them?
3. Are multiple routes available to drivers?

4. What are the size and topology (isolated junctions, linear arterial, grid) of the network?
5. What types of roadway users (cars, carpools, public transit vehicles, trucks, bicycles, pedestrians) should be considered?
6. What traffic control methods (regulatory signs, pretimed signals, actuated signals, real-time traffic-adaptive signals, and ramp-metering signals) should be considered?
7. Should oversaturated traffic conditions be considered?
8. Does the network involve specialized traffic control or intelligent transportation system (ITS) features that are not covered by the HCM?
9. What is the duration of the analysis period?
10. Do the geometric conditions of the roadway facility change during the analysis period?
11. Does the traffic demand fluctuate significantly during the analysis period?
12. Does the traffic control change during the analysis period?
13. What output and level of detail are anticipated from the tool?
14. What information is available for model input, model calibration, and validation?
15. Are multiple methods available for consideration in the analysis?

Examples of ITS features not covered by the HCM include traffic-responsive signal timing, traffic-adaptive control, dynamic ramp metering, dynamic congestion pricing, and strategies affecting the prevalence or duration of incidents with less than 10-min durations.

Assessing HCM Methodologies

Another essential step in the analysis tool selection process is to assess the capability of the existing HCM methodologies and to determine whether they can be applied (in whole or in part) to the issues that were raised in the project-scoping step. In addressing these issues, two major questions should be answered: What are the limitations of the HCM methodologies? Can the limitations be overcome? Limitations of the existing HCM methodologies for each facility type are identified in the procedural chapters of Volumes 2 and 3 of this manual. If an alternative tool is determined to be needed or advisable, the most appropriate tool must be selected.

Use the Limitations of the Methodology sections of Volume 2 and 3 chapters to assess the appropriateness of the HCM methodology for a given analysis.

Selecting a Traffic Analysis Tool

Each analytical or simulation model, depending on the application, has its own strengths and weaknesses. It is important to relate relevant model features to the needs of the analysis and determine which tool satisfies those needs to the greatest extent. Both deterministic and simulation-based tools could be candidates for overcoming HCM limitations. In most cases, however, deterministic tools will exhibit limitations similar to those of the HCM procedures, which are also deterministic. Deterministic tools also tend to work at the same macroscopic level as the HCM. Alternative deterministic tools fall mainly into the following categories:

Every traffic analysis tool, depending on the application, has its own strengths and weaknesses.

- Tools for signal-timing plan design and optimization,
- Proprietary deterministic models offering features not found in the HCM,

- *Other ITS devices.* In addition to the ITS elements in the traffic control category, tools may be able to model the effects of other ITS devices, such as in-vehicle navigation systems, dynamic message signs, incident management, smart work zones, or intervehicle communications.
- *Real-time process control features.* Many tools offer the ability to communicate directly with other processes invoked in either hardware or software. Examples include intersection signal controllers and large-scale network traffic management systems. Most highway capacity analysis projects will not require features of this type. However, when complex networks with ITS elements are involved, the ability of a simulation tool to communicate directly with the outside world might become a significant factor in the selection of the proper tool.

Above all, the analyst should review the user's guide for the selected tool to get a more detailed description of its characteristics.

User Interface

User interface considerations.

The user interface includes all of the features of a tool that supply input data from the user to the model and output data from the model to the user. Simulation tools vary in the nature of their user interface. To some extent, the suitability of the user interface is a matter of individual preference. However, a highly developed user interface can offer a better level of productivity for larger and more repetitive tasks. Selection criteria related to the user interface include

- The amount of training needed to master its operation,
- The extent to which it contributes to productive model runs,
- The extent to which it is able to import and export data between other processes and databases, and
- Special computational features that promote improved productivity.

The following are the principal elements associated with the user interface:

- *Inputs.* Most of the inputs required by the model will be in the form of data. In most cases, the input data will be entered manually. Most tools offer some level of graphic user interface to facilitate data entry. Some tools also offer features that import data directly from other sources.
- *Outputs.* Two types of outputs are available from simulation tools: graphics files and static performance measures. Graphics files provide graphics output, including animation, so that users can visually examine the simulation model results. Static performance measures provide output for numerical analysis. Both types of outputs may be presented directly to the user or stored in files or databases for postprocessing by other programs.
- *Multiple-run support.* The stochastic nature of simulation models requires multiple runs to obtain representative values of the performance measures. Chapter 7, Interpreting HCM and Alternative Tool Results, provides guidance on the number of runs required under specific conditions. The ability of a tool to support multiple runs is an important selection criterion. Multiple-run support includes processing functions

that perform a specified number of runs automatically and postprocessing functions that accumulate the results from individual runs to provide average values and confidence intervals.

Data Availability

The next criterion identifies data requirements and potential data sources so that the disparity between data needs and data availability can be ascertained. In general, microscopic models require more intensive and more detailed data than do mesoscopic and macroscopic models. Three different types of data are required to make the application of the traffic simulation model successful: data for model input, data for model calibration, and data for model validation.

Consider the kind of data required and the availability of the data in selecting a tool.

Data for Model Input

The basic data items required to describe the network and the traffic conditions to be studied can be categorized into four major groups:

1. *Transportation network data.* Simulation tools incorporate their network representation into the user interface, and some differences occur among tools. Most simulation models use a link-based scheme in which links represent roadway segments that are connected in some manner. Required link data include endpoint coordinates, link length, number of lanes per link, lane additions, lane drops, lane channelization at intersections, turning pockets, grade, and horizontal curvature. Connector data describe the manner in which the links are connected, including the permissible traffic movements, type of control, and lane alignment.
2. *Traffic control and ITS data.* Detailed control data should be provided for all control points, such as street intersections or freeway on- and off-ramps. Sign controls include YIELD signs, two-way STOP signs, and all-way STOP signs. Signal controls include pretimed signals, actuated signals, or real-time traffic-adaptive signals. Ramp-metering control methods include all of the modes described earlier. Timing data are required for all signal controls. Detector data such as type and location of the detector are required for actuated and traffic-adaptive signals. Any special ITS features involved in a project will create a need for additional data describing their parameters.
3. *Traffic operations data.* To represent the real-world traffic environment, most simulation tools take link-specific operations data as input, such as parameters that determine roadway capacity, lane use, lane restriction, desired free-flow speed, high-occupancy-vehicle lanes, parking activities, lane blockages, and bus transit operations.
4. *Traffic demand data.* Different tools may require traffic demand data in different formats. The most commonly used demand data are traffic demand at the network boundary or within the network, traffic turning percentages at intersections or freeway junctions, origin–destination (O-D) trip tables, path-based trips between origins and destinations, and traffic composition.

Data for Model Calibration

Calibration adjusts a model's vehicle, driver, and other characteristics so that the model can realistically represent the traffic environment being analyzed.

Calibration was defined previously as the process by which the analyst selects the model parameters that result in the best reproduction of field-measured local traffic operations conditions by the model. Vehicle and driver characteristics, which may be site-specific and require calibration, are the key parameters for microscopic traffic simulation models. Of course, the type of simulation model that is being used for a particular application determines the type of parameters that need to be calibrated. For example, in macroscopic traffic simulation models, the behavior of the drivers and the performance of the network are represented with more aggregate models, such as the speed–density relationship and the link input and output capacities. In that case, the parameters that need to be calibrated differ from those outlined above, but the process is fundamentally the same. For example, a specific application may require calibration of the parameters of the speed–density relationship of groups of links and the capacities of the network links.

These data take the form of scalar elements and statistical distributions that are referenced by the model. In general, simulation models are developed and calibrated on the basis of limited site-specific data. The development data may not be transferable and therefore may not accurately represent the local situation. In that case, the model results should be interpreted with caution, and the default parameters that must be overridden for better reflection of local conditions should be identified. Most simulation tools allow the analyst to override the default driver behavior data and vehicle data to improve the match with local conditions, thereby allowing for model calibration. The calibration process should be documented, traceable, and reproducible to promote a robust analysis.

1. *Driver behavior data.* Driver behavior is not homogeneous, and thus different drivers behave differently in the same traffic conditions. Most microscopic models represent stochastic or random driver behavior (from passive to aggressive drivers) by taking statistical distributions of behavior-related parameters such as desired free-flow speed, queue-discharge headway, lane-changing and car-following behavior, and driver response to advance information and warning signs.
2. *Vehicle data.* Vehicle data represent the characteristics and performance of the types of vehicles in the network. Different vehicle types (e.g., cars, buses, single-unit trucks, semitrailers) have different characteristics and performance attributes. They vary in terms of vehicle length, maximum acceleration and deceleration, fuel consumption rate, and emissions rate. All traffic simulation tools provide default vehicle characteristics and performance data. These data need to be overridden only when the local vehicle data are known to be different from the default data provided by the tool or when the default values do not provide reasonable results.

Data Sources

Data collection is costly. Analysts should explore all possibilities for leveraging previously collected data, with the caveat that the data should continue to be representative of current conditions. The analyst should identify which data are currently available and which data need to be collected in the field. Most static network, traffic, and control data can be collected from local agencies. Such data include design drawings for geometries, signal-timing plans, actuated controller settings, traffic volume and patterns, traffic composition, and transit schedules.

Ease of Use

Simulation models use assumptions and complex theories to represent the real-world dynamic traffic environment. Therefore, an input–output graphical display and debugging tools that are easily understood are important criteria to consider in selecting a tool. Although ease of use is important in a simulation tool, the fact that a particular tool is easy to use does not necessarily imply that it is the correct choice. The following five criteria can be considered in assessing the ease of use of a simulation tool:

- *Preprocessor:* input data handling (user-friendly preprocessor);
- *Postprocessor:* output file generation for subsequent analysis;
- *Graphics displays:* graphic output capabilities, both animated and static;
- *Online help:* quality of online help support; and
- *Calibration and validation:* ability to provide guidelines and data sets for calibration and validation.

Required Resources

The following issues with regard to resources should be addressed in selecting a traffic analysis tool:

- *Costs to run the tool.* Examples are costs for data collection and input preparation, hardware and software acquisition, and model use and maintenance.
- *Staff expertise.* Intelligent use of the tool is the key to success. The analyst should understand the theory behind the model to eliminate improper use and avoid unnecessary questions or problems during the course of the project.
- *Technical support.* Quality and timely support are important in the acquisition of a tool.

User Applications and Past Performance

Credibility and user acceptance of a tool are built on the tool's past applications and experiences. No tool is error-free at its first release, and all require continuous maintenance as well as periodic enhancements.

Verification and Validation

Assessment of how extensively a given model has been verified is important. In many cases, but not all, simulation models are also validated as part of the formulation and development process. Certainly, validated models are nominally better to use than those that have not been validated. Generally, models that have been in use for some time are likely to have been assessed and validated by various researchers or practitioners who are using them. Evidence of validation in professional journals and periodicals is useful.

APPLICATION GUIDELINES FOR SIMULATION TOOLS

This section presents general guidance for the use of simulation-based traffic analysis tools for capacity and performance analysis. More detailed guidance for the application of these tools to specific facilities is presented in the procedural chapters of Volumes 2 and 3. Additional information, including sample applications, may be found in the Volume 4 supplemental chapters, the *HCM Applications Guide*, and the *Traffic Analysis Toolbox*, as mentioned previously.

The Traffic Analysis Toolbox *is available at http://ops.fhwa.dot.gov/trafficanalysistools/.*

After the project scope has been determined and the tool has been selected, several steps are involved in applying the tool to produce useful results.

Assembling Data

Data assembly involves collecting the data required (but not already available) for the selected tool. Data collection is costly. Analysts should capitalize on previous modeling efforts and identify data available through local agencies. When existing data are assembled, users should develop a comprehensive plan for collecting data that are missing. In some cases, a pilot data collection effort may be needed to ensure that the data collection plan is workable before a full-scale effort is conducted.

An important part of the data assembly process is a critical review of all data items to ensure the integrity of the input data set. Of special concern are the continuity of traffic volumes from segment to segment and the distribution of turning movements at intersections and ramp junctions. Each data item should be checked to ensure that its value lies within reasonable bounds.

Entering Data

Once all required data are in hand, the next step is to create the input files in a format required by the selected tool. The following are the most commonly used methods for creating input files:

- *Importing from a traffic database.* Many analysts have large amounts of data in a variety of formats for the general purpose of traffic analysis. Such databases can be used to create input files.
- *Converting from the existing data of other tools.* Many traffic models use the same or similar data for modeling purposes so that these data may be shared. Some traffic simulation tools are accompanied by utility programs that allow the user to convert data into input files required by other tools.
- *Entering the data from scratch.* Many traffic analysis tools have their own specific input data preprocessors, which aid the analyst with input data entry and review. These advanced features of the input data preprocessor eliminate cumbersome coding efforts. In addition, some input preprocessors include online help features.

Calibrating and Validating Models

The model should be run with the data set describing the existing network and traffic scenarios (i.e., the baseline case), and the simulation results should then be compared with the observed data collected in the field. The primary objective of this activity is to adjust the parameters in the model so that simulation results correspond to real-world situations.

The initial model run should (a) represent the initial state of the traffic environment before statistics are collected, (b) cover the entire analysis period, and (c) specify the dynamic input conditions describing the traffic environment (for models capable of handling time-varying input).

Three critical issues must be addressed when an initial simulation model run is conducted for the baseline case. First, the model should represent the initial state of the traffic environment before any statistics are collected for analysis. Second, the time should be long enough to cover the entire analysis period. Third, if the model can handle time-varying input, the analyst should specify, to the extent possible, the dynamic input conditions that describe the traffic environment. For example, if 1 h of traffic is to be simulated, the analyst should always specify the variation in demand volumes over that hour at an appropriate level of detail rather than specifying average, constant values of volume.

In addition, the analyst should know how to interpret the simulation model results, draw inferences from them, and determine whether they constitute a reasonable and valid representation of the traffic environment. Given the complex processes taking place in the real-world traffic environment, the user must be alert to the possibilities that the model's features may be deficient in adequately representing some important process; that the specified input data, calibration, or both are inaccurate or inadequate; that the results provided are of insufficient detail to meet the project objectives; that the statistical analysis of the results is flawed (as discussed in the following section); or that the model has bugs or that some of its algorithms are incorrect, thereby necessitating revision. If animation displays are provided by the model, this option should always be exercised to identify any anomalies.

If the simulation model results do not reasonably match the observed data collected in the field, the user should identify the cause-and-effect relationships between the observed and simulated data and the calibration parameters and perform calibration and validation of the model. Information on calibrating and validating models may be found in the *Traffic Analysis Toolbox*.

Special Considerations for DTA

The term "traffic assignment" traditionally refers to the process of computing path demands, or path input flows, given a network and an O-D demand matrix (trip table). In microscopic simulation models, this process is implemented as a route-choice model that is executed independently for each driver (vehicle) in the simulation. Routes and route flows may also be implicitly represented in a model by splitting rates, which are turning proportions at nodes by destination. The use of explicit routes to move vehicles through the simulation obviates the use of turning proportions at nodes. Route flows can have a significant impact on model outputs such as LOS, since they play a key role in determining the local traffic demand on any given section of road.

Regardless of the implementation, traffic assignment is relevant whenever demand is defined in the form of an O-D matrix (static or time-varying) and multiple routes are available for some O-D pairs. It is particularly relevant when congestion affects the travel times on some of these routes. DTA produces time-varying path flows (or splitting rates) by using a dynamic traffic model that is either mesoscopic or microscopic. DTA models normally permit the demand matrix to be time-varying as well. The assignment model (routing decision) is based on a specific objective, which is predominantly the minimization of travel time, but it will also take other factors such as travel cost (e.g., tolls or congestion pricing) and travel distance into consideration.

A fundamental issue concerning the role of travel time in route choice is that the actual travel time from origin to destination cannot be known in advance: it results from the collective route choices of all the drivers. Thus, the input to the routing decision (travel time) depends on the decision itself (route choice), forming a logical cycle. This type of problem can be solved with an iterative algorithm that repeats the simulation several (or many) times over, imitating the day-to-day learning process of drivers in the real world. At each iteration (or "day") the assignment is adjusted until the route-choice decisions are consistent with the experienced travel times: this is referred to as the user-optimal solution. In practice, an approximation to the user-optimal route flows is often determined by using a "one-pass" (noniterative) assignment in which drivers repeatedly reevaluate their routes during a single simulation run. The choice of method depends on network characteristics and modeling judgment.

The assignment (routing) component of a DTA model may be deterministic or stochastic in nature, independent of whether the traffic model is deterministic or stochastic. In general, both approaches can generate good results as long as they produce route choices that are consistent with the routing objective, for example, the minimization of generalized travel cost. The generalized cost is determined from the combination of a range of factors, such as travel time, travel distance, and direct costs (e.g., tolls), by applying relative weights to each of these factors, which typically differ by user class.

DTA applications are not trivial. Whereas single route applications are typically implemented by one analyst, DTA applications to large-scale systems are more likely to involve a team of analysts with a broader range of skills and experience. Several references on DTA are available (e.g., *15, 16*).

Analyzing Output

Proper output analysis is one of the most important aspects of any study using a simulation model. A variety of techniques are used, particularly for stochastic models, to arrive at inferences that are supportable by the output.

When the model is calibrated and validated, the user can conduct a statistical analysis of the simulation model results for the baseline case with calibrated parameters. If the selected simulation model is stochastic in nature, simulation model results produced by a single run of the model represent only point estimates in the sample population. Typical goals of data analysis using output from stochastic-model experiments are to present point estimates of the performance measures and to form confidence intervals around these estimates. Point estimates and confidence intervals for the performance measures can be obtained from a set of replications of the system by using independent random number streams. The analyst should refer to the *Traffic Analysis Toolbox* for details on the design and analysis of stochastic simulation models.

Analyzing Alternatives

When satisfactory simulation model results are obtained from the baseline case, the user can prepare data sets for alternative cases by varying geometry, controls, and traffic demand. If the model is calibrated and validated on the basis of the observed data, values of the calibrated parameters should also be used in the alternatives analysis, assuming that driver behavior and vehicle characteristics in the baseline case are the same as those in the alternative cases.

Traffic simulation models produce a variety of performance measures for alternatives analysis. As discussed previously, the user should identify what model performance measures and level of detail are anticipated. These performance measures, such as travel time, delay, speed, and throughput, should be quantifiable for alternatives analysis. Some tools provide utility programs or postprocessors, which allow users to perform the analysis easily. If animation is provided by the tool, the user can gain insight into how each alternative performs and can conduct a side-by-side comparison graphically.

4. REFERENCES

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APPENDIX A: DEVELOPING LOCAL DEFAULT VALUES

Default values are generally used for HCM applications that do not require the accuracy provided by a detailed operational evaluation.

A default value is a constant to be used in an equation as a substitute for a field-measured (or estimated) value. Default values can be used for input parameters or calibration factors. The value selected should represent a typical value for the conditions being analyzed. Default values are generally used for planning, preliminary engineering, or other applications of the HCM that do not require the accuracy provided by a detailed operational evaluation (*A-1*). They can be applied to any of the modes addressed by the HCM.

Default values should not be applied for input variables that can significantly influence the analysis results.

Local default values can be developed by conducting measurements of "raw data" in the geographic area where the values are to be applied. Default values are usually developed for roadway or traffic characteristics to identify typical conditions of input variables for planning or preliminary engineering analysis. Default values should not be applied for input variables that can significantly influence the analysis results. For interrupted-flow facilities, these sensitive input variables include peak hour factor, traffic signal density, and percent heavy vehicles. For uninterrupted-flow facilities, these sensitive input parameters include free-flow speed and the number of travel lanes. In developing generalized service volume tables for daily service volumes, the *K*- and *D*-factors selected must be consistent with measured local values.

When local default values are developed, the raw data should be collected during the same time periods that will be used for analysis—typically during weekday peak periods. In some cases, the peak 15-min period is recommended as the basis for computation of default values because this time period is most commonly used for capacity and LOS analysis.

Input parameters that describe the facility type, area type, terrain type, and geometric configuration (such as lane width, segment length, and interchange spacing) are readily available to the analyst. Default values for these parameters should not be used.

REFERENCE

This reference can be found in the Technical Reference Library in Volume 4.

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APPENDIX B: DEVELOPING LOCAL SERVICE VOLUME TABLES

INTRODUCTION

As discussed in the body of this chapter, service volume tables can provide an analyst with an estimate of the maximum number of vehicles a system element can carry at a given LOS. The use of a service volume table is most appropriate in certain planning applications in which evaluation of every segment or node within a study area is not feasible. Once potential problem areas have been identified, other HCM tools can be used to perform more detailed analyses for just those locations of interest.

This appendix focuses on the automobile mode. To the limited extent that modal demand is an input to nonautomobile modes' LOS procedures, this material could also be applied to nonautomobile modes.

To develop a service volume table, the analyst needs to develop a default value for each input parameter used by the system element's HCM method. The choice of default value can have a significant impact on the resulting service volumes. For this reason, great care should be used to develop default values that the analyst believes are most appropriate for local conditions. When results are particularly sensitive to a particular parameter, a range of default values should be considered for that parameter. The application of sensitivity analyses is discussed in Chapter 7, Interpreting HCM and Alternative Tool Results.

When the service volume table is applied, the unlikelihood of a match between all of the input parameters for the various roadway segments being evaluated and the default inputs needs to be recognized. Accordingly, conclusions drawn from the use of service volume tables should be considered and presented as rough approximations.

A specific roadway's characteristics are unlikely to match exactly the default values used to generate a service volume table. Therefore, conclusions drawn from such tables should be considered to be rough approximations.

TABLE CONSTRUCTION PROCESS

Service volume tables are generated by applying software to back-solve for the maximum volume associated with a particular LOS, given the analyst's selected set of default values. The procedure is as follows (*B-1*):

1. Determine all of the nonvolume default values to be used in developing the service volume table (e.g., number of lanes, peak hour factor, percentage of heavy vehicles, area type, *K*- and *D*-factors), in accordance with the guidance in Appendix A.
2. Identify the threshold value associated with the system element's service measure for LOS A by using the LOS exhibit in the Volume 2 or Volume 3 chapter that covers that system element. For example, a density of 11 pc/mi/ln is the maximum density for LOS A for a basic freeway segment.
3. Compute the service measure for a volume of 10 veh/h for an hourly volume table, or 100 veh/h for a daily volume table. If the result exceeds the LOS A threshold value, then LOS A is unachievable. Repeat Steps 2 and 3 for the next LOS (e.g., LOS B) until an achievable LOS is found, then continue with Step 4.
4. Adjust the input volume until the highest volume that achieves the LOS is found. Test volumes should be a multiple of at least 10 for hourly volume tables and at least 100 for daily volume tables. If the table is being created

by manually applying software, the analyst can observe how closely the service measure result is converging toward the LOS threshold and can select a test volume for the next iteration accordingly. If the table generation function is being added to software, the automated method described below can be used to converge on the service volume.

5. Identify the threshold value for the next LOS and repeat Steps 4 and 5 until threshold volumes have been found or unachievability has been determined for each LOS.
6. If a daily volume table is being created, divide the hourly threshold volumes by the selected *K*- and *D*-factors and round down to a multiple of at least 100.
7. If desired, change the value used for one of the input parameters (e.g., number of lanes) and repeat Steps 2 through 6 as many times as needed to develop service volumes for all desired combinations of input values.

The following is an automated method for finding threshold values:

1. Label the first achievable test volume *Vol 1*.
2. Select a second iteration volume (*Vol 2*) by doubling Vol 1.
3. Compute the service measure value for Vol 2.
4. If the resulting service measure value is lower than the LOS threshold, replace Vol 1 with Vol 2 and select a new Vol 2 with double the current Vol 2 value. Repeat Steps 3 and 4 until the service measure result is greater than the desired LOS threshold.
5. Use the bisection method described in Steps 6 through 10 (*B-1*) or another more efficient numerical method to converge on the service volume.
6. Compute the volume halfway between Vol 1 and Vol 2 and label it *Vol 3*.
7. Compute the service measure value for Vol 3.
8. If the service measure result for Vol 3 is greater than the desired LOS threshold, replace Vol 2 with Vol 3.
9. If the LOS result for Vol 3 is lower than the desired LOS threshold, replace Vol 1 with Vol 3.
10. Is the range between Vol 1 and Vol 2 acceptable? If yes, stop and use the average of Vol 1 and Vol 2. If not, repeat Steps 6 through 9.
11. If an hourly volume table is being generated, round the result of Step 10 down to a multiple of at least 10. If a daily volume table is being generated, divide the result of Step 10 by the selected *K*- and *D*-factors and round the result down to a multiple of at least 100.

REFERENCE

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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.

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.

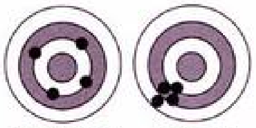
Finally, when both HCM-based and alternative tools are used in an analysis, or when a performance measure produced by an alternative tool is used to determine level of service (LOS), it is important to ensure that the alternative tool's measures are defined in the same way as the HCM measures. Alternative 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.

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



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

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

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.

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.

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

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

- *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.

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

Sources of uncertainty in model outputs.

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.

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.

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

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.

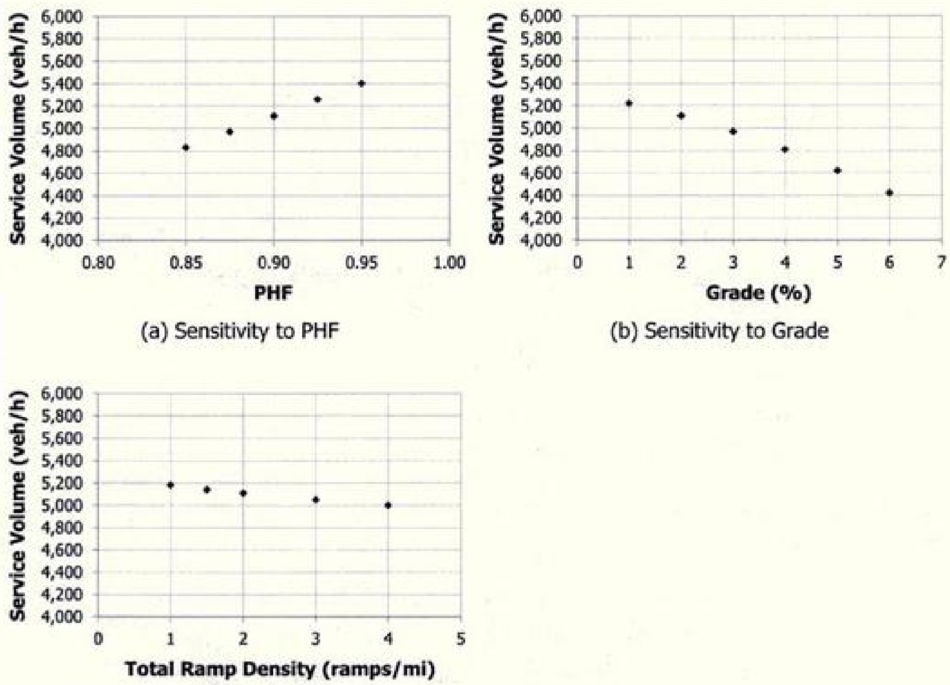
Exhibit 7-1 illustrates a sensitivity analysis for selected inputs to the basic freeway segment method. A typical application would be a planning study for a future freeway, where not all the inputs are known exactly. The output being tested is the service volume (in vehicles per hour, veh/h) for LOS 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*).

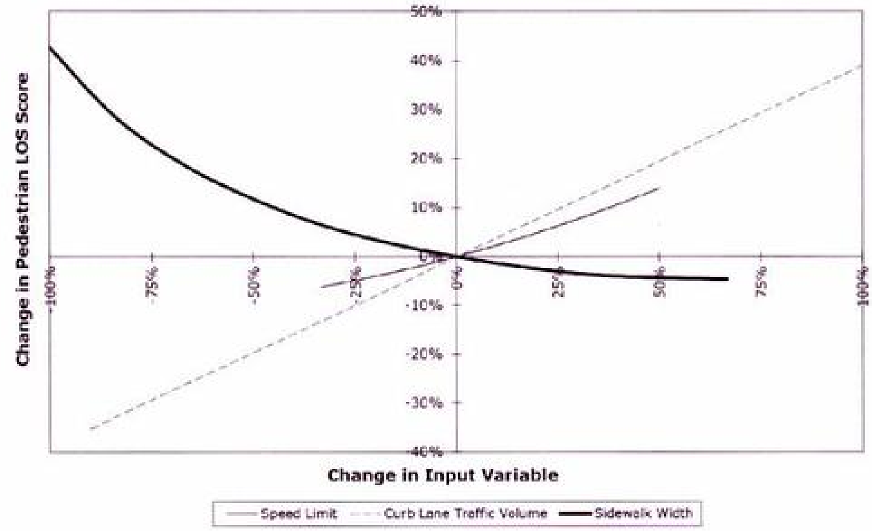
As shown in Exhibit 7-1(a) and Exhibit 7-1(b), LOS D service volumes for basic freeway segments are moderately sensitive to both PHF and grade across the reasonable ranges of values for those inputs, with the highest service volumes 11% and 14% higher than the lowest service volumes, respectively. Consequently,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

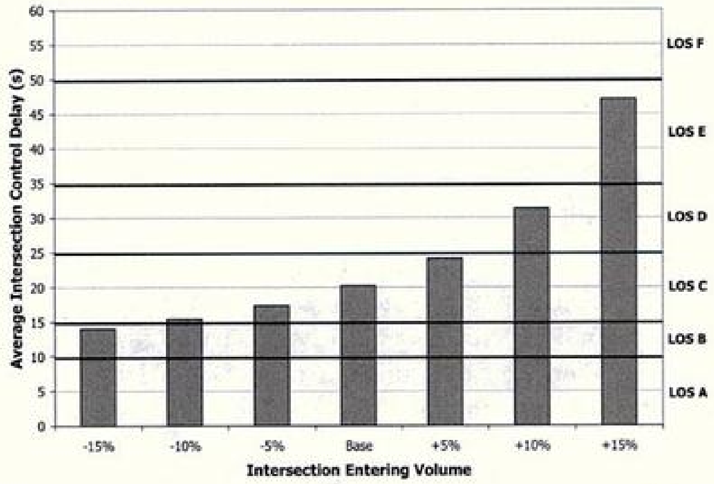
Exhibit 7-2
Example Sensitivity Analysis of Urban Street Link Pedestrian LOS Score



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.

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.

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.

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.

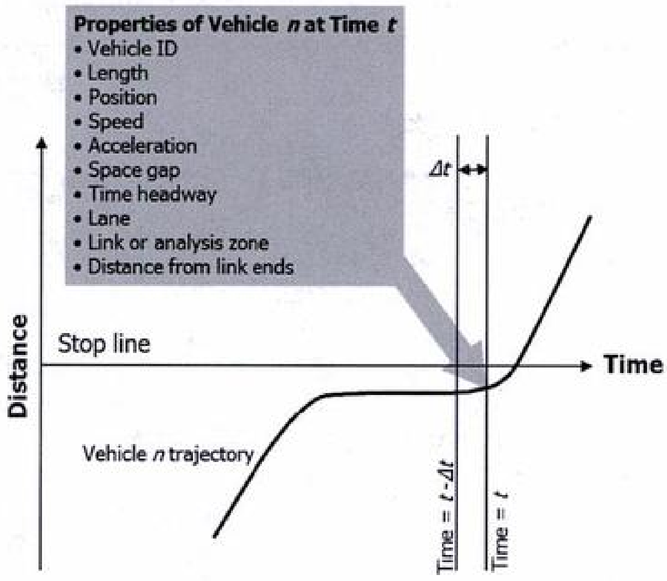
Mathematical Properties of Vehicle Trajectory

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

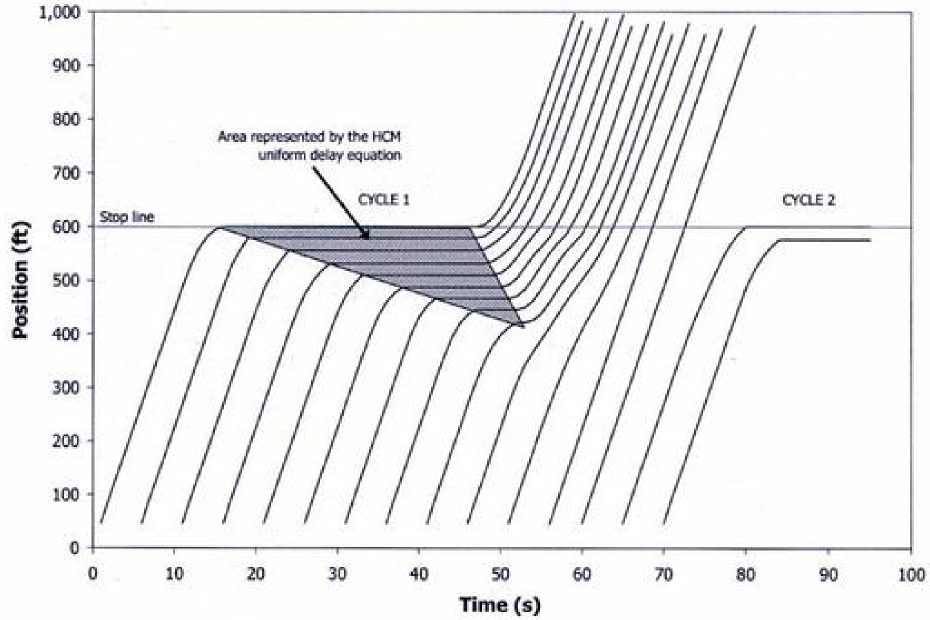
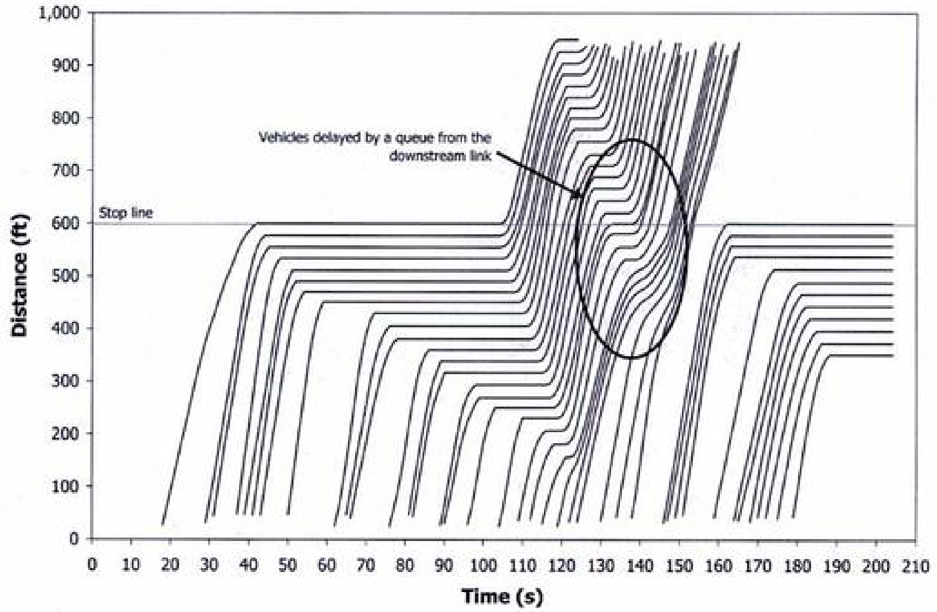


Exhibit 7-7
Queue Backup from a Downstream Signal



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

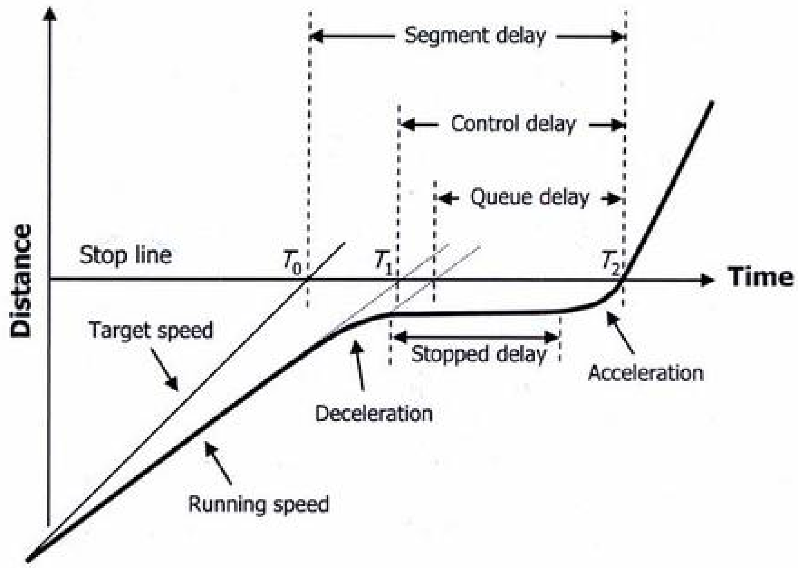
Several delay definitions were presented previously. These definitions may be interpreted in terms of vehicle trajectories on the basis of longitudinal trajectory analysis. In all cases, the delay is determined for each time step and accumulated over the entire time the vehicle was in a specified segment.

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:

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

Equation 7-2

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:

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

Equation 7-3

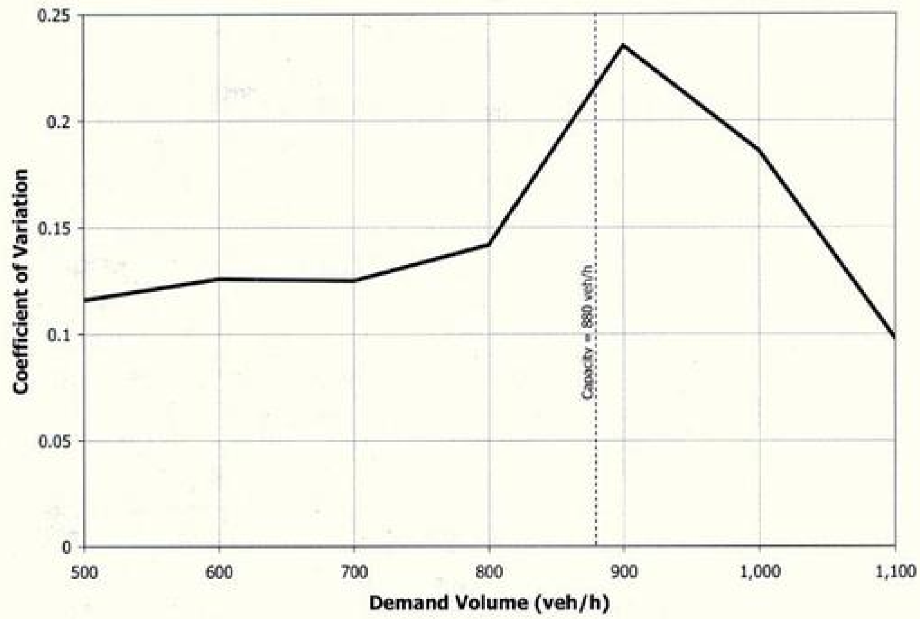
A few statistically oriented sites on the Internet offer online calculators for determining required sample sizes.

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		Minutes per Mile		Average Speed (mi/h)
		Delay	Total	Delay	Total	
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 alternative tools is seldom attainable because of differences in definitions, modeling approaches, and computational methodologies.

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:

- 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

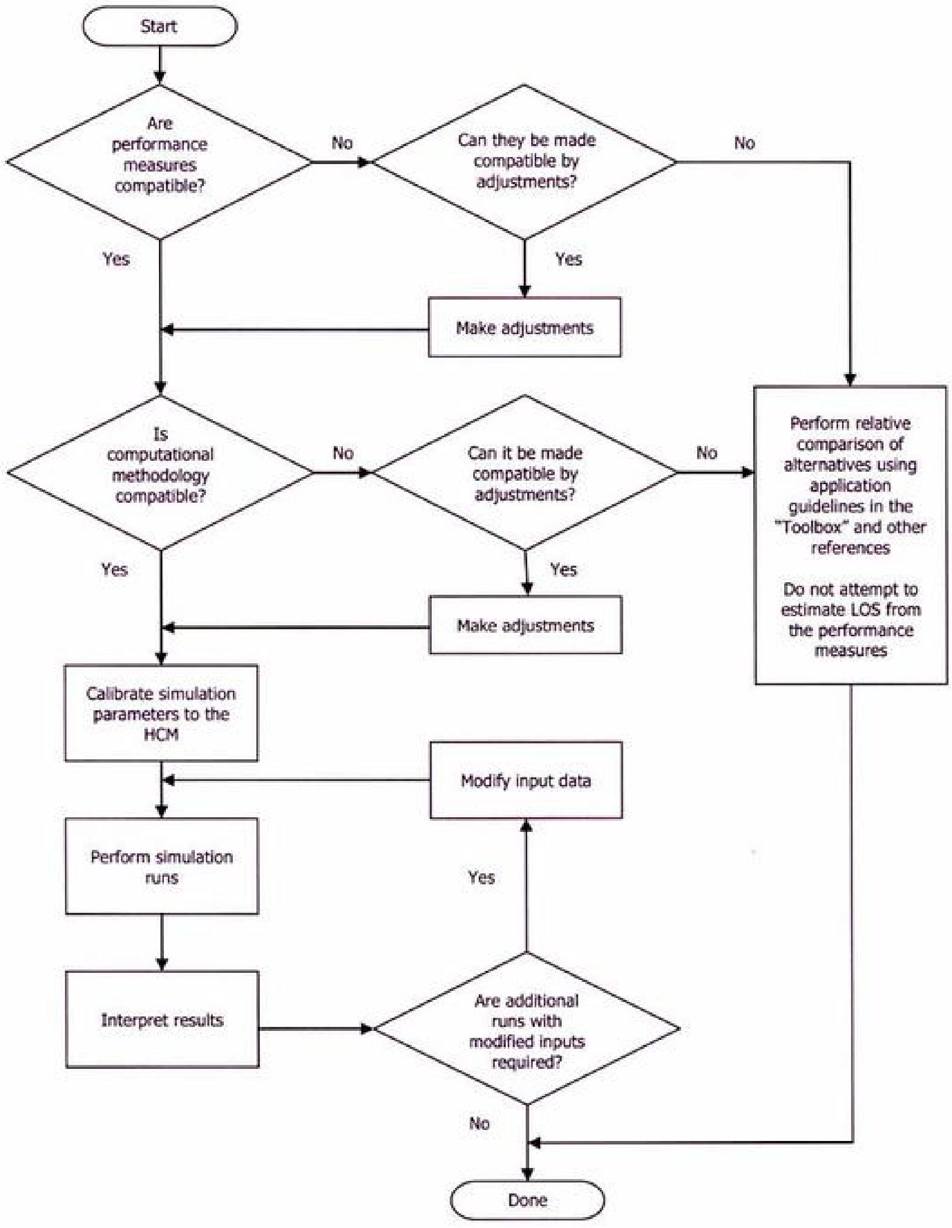
The application framework for alternative tools is presented in the form of a flowchart in Exhibit 7-11. This framework applies to all the procedural chapters in Volumes 2 and 3.

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

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.

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.

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.

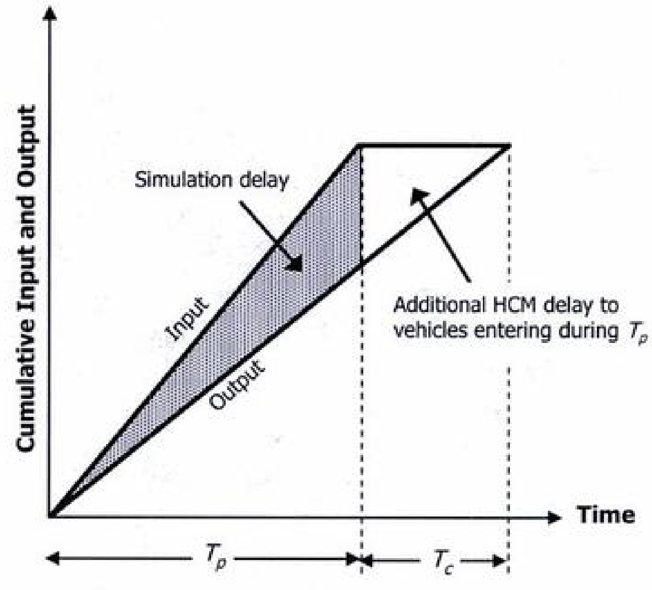
The issues are more conspicuous when the d/c ratio is greater than 1.00 for short periods. In this case, queues build up and the analysis (either HCM or simulation) must define temporal boundaries that begin and end without congestion. It is also desirable, but not essential, that the spatial boundaries 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.

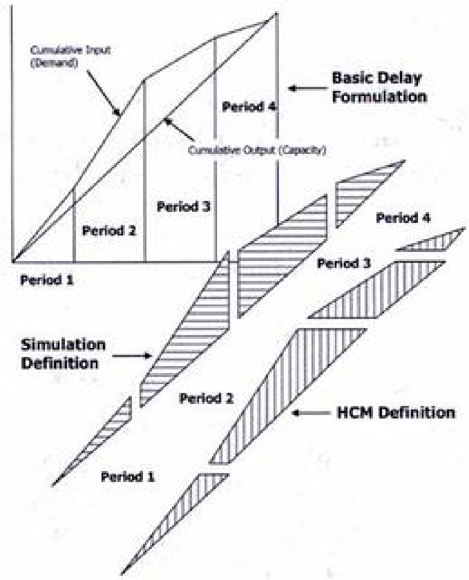
Delay for Multiperiod Oversaturation

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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CHAPTER 8
HCM PRIMER

CONTENTS

LIST OF EXHIBITS

1. INTRODUCTION

OVERVIEW

The *Highway Capacity Manual 2010* (HCM) is the fifth edition of this fundamental reference document. Its objectives are threefold:

1. To define performance measures and describe survey methods for key traffic characteristics,
2. To provide methodologies for estimating and predicting traffic-related performance measures, and
3. To explain methodologies in a manner that allows readers to understand the factors that affect multimodal roadway operations.

The travel modes covered by the HCM consist of the *motorized vehicle, pedestrian,* and *bicycle* modes, as well as *public transit* service in a multimodal context. The motorized vehicle mode includes motorcycles; light vehicles such as automobiles and sport-utility vehicles; and heavy vehicles such as trucks, recreational vehicles, and buses.

HCM methodologies can be applied both to *uninterrupted-flow* roadways, such as freeways, multilane rural highways, and two-lane rural highways, and to *interrupted-flow* roadways, primarily urban streets and the intersections located along those streets. Methodologies are also provided for evaluating off-street pedestrian and bicycle facilities. The HCM can be applied to *undersaturated* conditions (where traffic demand is less than a roadway's capacity) and, in certain situations, to *oversaturated* conditions (where demand exceeds capacity).

Uninterrupted-flow facilities have no fixed causes of delay or interruption external to the traffic stream.

Interrupted-flow facilities have fixed causes of periodic delay or interruption to the traffic stream, such as traffic signals, roundabouts, and STOP signs.

The HCM presents the best available techniques at the time of publishing for determining roadway capacity and level of service (LOS) that have been proved to work in the United States and validated by a group of independent experts. However, the HCM does not endeavor to establish a legal standard for highway design or construction.

CHAPTER PURPOSE AND ORGANIZATION

Chapter 8 is written for a nontechnical audience and is a synopsis of Volume 1 of the HCM.

This chapter is written for an audience (e.g., decision makers) who may be regularly presented with the results of HCM analyses and who may have no formal training in transportation engineering, but who need to understand basic HCM concepts, terminology, and methodological strengths and weaknesses in making informed decisions. This chapter addresses the following:

- Section 2 covers basic traffic operations terminology and concepts.
- Section 3 presents concepts related to quality of service (how well a transportation facility or service operates from a traveler's perspective).
- Section 4 describes the different levels of analysis that can be performed with the HCM and provides guidance on selecting an analysis tool and interpreting and presenting the results from an HCM analysis.
- Section 5 discusses companion documents to the HCM and issues to consider when the HCM is used in a decision-making process.

The HCM can be applied at the planning, preliminary engineering, operations, and design levels of analysis.

2. HIGHWAY OPERATIONS CONCEPTS

This section introduces basic traffic engineering concepts that form the foundation of technical analyses that apply the HCM or other analysis tools. The section describes the two main types of traffic flow analyzed by the HCM—uninterrupted flow (e.g., freeways) and interrupted flow (e.g., urban streets)—along with their characteristics, the HCM methodologies available for analyzing them, and key performance measures produced by these analyses. This section also summarizes how the different travel modes using a roadway interact with each other and how they affect the roadway's overall operation.

CAPACITY AND TRAFFIC FLOW CONCEPTS

Capacity Definition

Capacity is the maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions. This one-sentence definition covers a variety of diverse topics, each discussed below:

- *Roadway conditions* include the number and width of lanes, shoulder width, and the roadway's horizontal and vertical alignment. Substandard lane and shoulder widths result in a permanently lower capacity than could be achieved with standard widths. Work zones and incidents (e.g., stalls, crashes) that close or block travel lanes or shoulders reduce roadway capacity temporarily, but their effects can last much longer than the actual work zone or incident event.
- *Environmental conditions* include weather and lighting. The HCM assumes good weather as a base but also provides guidance on evaluating the impact of inclement weather on roadway operations—for example, as part of an analysis of travel time reliability.
- *Traffic conditions* include the proportion of heavy vehicles (e.g., trucks) in the traffic stream, the proportion of roadway users who are regular users, turning-movement patterns at intersections, and the distribution of vehicles between lanes and directions of a roadway.
- *Control conditions* include the types of traffic control used at intersections (i.e., traffic signals, STOP signs, or YIELD signs), the amount of green time allocated to a particular movement at a traffic signal, and restrictions on the use of certain lanes (e.g., part-time restrictions on parking, truck prohibitions in the left lane of a freeway).

In comparison with passenger cars, heavy vehicles take up more roadway space and have poorer operating characteristics.

As traffic flow approaches a roadway's capacity, traffic speeds decrease and—on uninterrupted-flow roadways—vehicles follow each other at closer headways. When traffic demand exceeds the roadway's capacity, a breakdown occurs, as evidenced by sharply decreased travel speeds and a growing queue of vehicles.

Reasonable expectancy is the basis for defining capacity. A given system element's capacity is a volume or flow rate that can be achieved repeatedly under the same prevailing conditions, as opposed to being the maximum value that might ever be observed. Since the prevailing conditions (e.g., weather, mix of heavy vehicles) will vary within the day or from one day to the next, a system element's capacity at a given point in time will also vary—a traffic flow that can be served at one point in time may result in a breakdown at a different time.

Base Capacity and Actual Capacity

The base capacity values presented in the HCM—for example, 2,400 vehicles per hour per lane on a freeway with a 75-mph free-flow speed, or 1,900 vehicles per hour of green at a traffic signal—are just that: *base values*. These values incorporate, among other factors, ideal roadway geometry, a traffic stream composed entirely of passenger cars, and good weather. To the extent that conditions vary from the ideal—truck presence, an upgrade, constrained shoulder width, nonfamiliar roadway users, or severe weather, for example—actual capacity will be reduced from the base value. Driver characteristics (e.g., willingness to tolerate close headways) may vary locally, and the HCM provides a means of calibrating its methods to account for local conditions.

The HCM's base capacity values represent ideal conditions; HCM methods reduce capacity to reflect nonideal conditions. HCM methods can also be calibrated to account for local conditions.

Volume and Flow Rate

HCM analyses typically evaluate the peak 15 minutes of an analysis hour. Traffic demands usually fluctuate over the course of an hour, so a roadway that could theoretically accommodate a given *hourly volume* of evenly arriving vehicles may break down when a shorter-term peak in demand occurs. The effects of a breakdown can extend far beyond the time during which demand exceeded capacity, can take several hours to dissipate, and may spread well beyond the original point of breakdown. The HCM addresses this peaking phenomenon by using *flow rates* that represent the equivalent hourly volume that would be observed if the peak 15-minute demand was sustained over an entire hour. A 15-minute analysis period accommodates most variations in flow without producing an excessively conservative estimate of capacity.

Traffic demands used in HCM analyses are typically expressed as flow rates *that represent four times the peak 15-minute traffic demand.*

Volume and Demand

Volume and flow rate help quantify *demand,* that is, the number of users (e.g., vehicles, persons) who *desire* to use a given portion of roadway during a specific time period, typically 1 hour or 15 minutes. Traffic volumes observed in the field may not reflect actual demand, because capacity constraints upstream of the count location may limit the number of vehicles that *can* reach the count location.

Demand relates to the number of vehicles that would like to be served by a roadway element, while volume relates to the number that are actually served.

Demand is typically the desired input to HCM analyses. (An exception might be the analysis of traffic conditions beyond a bottleneck that is not planned to be removed.) Only when conditions are *undersaturated* (i.e., demand is less than capacity) and no upstream bottlenecks exist can demand at a location be assumed equivalent to the measured volume at that location. Where bottlenecks exist, neglecting to use demand as an input to an HCM method will produce results that underestimate the presence and extent of congestion. In other words, using observed volumes instead of demand will likely result in inaccurate HCM results.

Vehicle Capacity and Person Capacity

Persons per hour, passenger car equivalents per hour, and vehicles per hour are all measures that can define capacity. The concept of person flow is important (*a*) in making strategic decisions about transportation modes in heavily traveled corridors and (*b*) in defining the role of transit and high-occupancy-vehicle priority treatments. Person capacity and person flow weight each vehicle type in the traffic stream by the number of occupants carried.

UNINTERRUPTED-FLOW ROADWAYS

Characteristics

Uninterrupted-flow roadways have no fixed causes of delay or interruptions to the traffic stream such as traffic signals. Freeways and their components operate under the purest form of uninterrupted flow. There are no fixed interruptions to traffic flow, and access is controlled and limited to ramp locations. Multilane highways and two-lane highways can also operate under uninterrupted flow in long segments; however, examination of points along those highways where traffic may need to slow or stop (e.g., intersections where the highway is controlled by traffic signals, STOP signs, or YIELD signs) may also be necessary.

The traffic stream on uninterrupted-flow facilities is the result of individual vehicles interacting with each other and the facility's geometric characteristics. The pattern of flow is generally controlled only by the characteristics of the land uses that generate the traffic using the facility, although freeway management and operations strategies—such as ramp metering, freeway auxiliary lanes, truck lane restrictions, variable speed limits, and incident detection and clearance—can influence traffic flow. Operations can also be affected by environmental conditions, such as weather or lighting; by pavement conditions; and by the occurrence of traffic incidents (*1*, *2*).

"Uninterrupted flow" describes the type of facility, not the quality of the traffic flow at any given time. A freeway experiencing stop-and-go congestion, for example, is still an uninterrupted-flow facility, despite the congestion.

HCM Methodologies

The HCM provides methodologies for the following uninterrupted-flow roadway elements:

- *Freeway facilities.* An extended length of a single freeway composed of a set of connected basic freeway, weaving, and merge and diverge segments.
- *Basic freeway segments.* The portions of a freeway outside the influence area of any on- or off-ramps.
- *Freeway weaving segments.* The portions of a freeway where an on-ramp is closely followed by an off-ramp and entering or exiting traffic must make at least one lane change to enter or exit the freeway.

- *Freeway merge and diverge segments.* The portions of a freeway where traffic enters or exits without having to change lanes to enter or leave a through traffic lane.
- *Multilane highways.* Higher-speed facilities, with two or more lanes in each direction, without full access control (i.e., traffic can enter or exit via at-grade intersections, which may or may not be signal-controlled).
- *Two-lane highways.* Facilities with mostly one lane of travel per direction, with motorists using passing lanes, turnouts, or the opposing lane (where allowed by regulation and opposing traffic) to pass slower vehicles.

Performance Measures

The following are key performance measures produced by the HCM that can be used to evaluate the operation of uninterrupted-flow roadways:

- *Density* is typically defined by the average number of vehicles (or passenger car equivalents) per lane mile of roadway. The denser the traffic conditions, the closer vehicles are to each other and the harder it is for vehicles to change lanes or maintain a constant speed. Density is frequently used to evaluate freeways and multilane highways.
- *Speed* reflects how fast motorists can travel. The speed at which a motorist would travel along an uninterrupted-flow roadway under low-volume conditions is known as the *free-flow speed.* Drivers experience *delay* when their travel speed is less than the free-flow speed, which is a result of traffic demands approaching or exceeding the roadway's capacity. Speed is used to evaluate all kinds of uninterrupted-flow roadways.
- *Travel time reliability* measures reflect the consistency (or lack thereof) of travel times or speeds over a long time frame (e.g., a year). Reliability measures provide an important contrast to traditional traffic operations performance measures that report average conditions; reliability measures indicate the range of possible conditions that may occur, which may differ considerably from the average condition.
- *Percent time-spent-following* is a measure specific to two-lane highways. It represents the freedom to maneuver and the comfort and convenience of travel. It is the average percentage of travel time that vehicles must travel in platoons behind slower vehicles because of the inability to pass.
- *Volume-to-capacity (v/c) ratio* reflects how closely a roadway is operating to its capacity. By definition, the volume of traffic using a roadway cannot exceed the roadway's capacity. Therefore, the *v/c* ratio is actually a *demand-to-capacity (d/c)* ratio. However, *v/c* ratio is the historically used term. A *v/c* ratio that exceeds 1.00 indicates that more vehicles demand to use a roadway than can be accommodated.

INTERRUPTED-FLOW ROADWAYS

Characteristics

Interrupted-flow facilities have fixed causes of periodic delay or traffic stream interruption, such as traffic signals, roundabouts, and STOP signs. Urban streets are the most common form of this kind of facility. Exclusive pedestrian and bicycle facilities are also treated as interrupted flow, since they may occasionally intersect other streets at locations where pedestrians and bicyclists are not automatically granted the right-of-way.

The traffic flow patterns on an interrupted-flow facility are the result of vehicle interactions, the facility's geometric characteristics, the traffic control used at intersections, and the frequency of access points to the facility. Traffic signals, for example, allow designated movements to occur only during certain portions of the signal cycle (and, therefore, only during certain portions of an hour). This control creates two significant outcomes. First, time affects flow and capacity, since the facility is not available for continuous use. Second, the traffic flow pattern is dictated by the type of control used. For instance, traffic signals create platoons of vehicles that travel along the facility as a group, with significant gaps between one platoon and the next. In contrast, all-way STOP-controlled intersections and roundabouts discharge vehicles more randomly, creating small (but not necessarily usable) gaps in traffic at downstream locations (*1*, *3*).

HCM Methodologies

The HCM provides methodologies for the following roadway elements:

- *Urban street facilities,* which are extended sections of roadway whose operation is strongly influenced by traffic signals or other traffic control. Facilities are formed by two or more consecutive *urban street segments,* typically street sections from one traffic signal to the next. Roundabouts and STOP-sign control on the urban street can also define the end of a segment. Segments are the basic analysis unit for multimodal analyses.
- *Signalized intersections.*
- *Interchange ramp terminals,* which are two closely spaced intersections of freeway ramps and surface streets, where the management of queues between the two intersections is a key concern.
- *Alternative intersections,* where one or more turning movements are rerouted to secondary intersections. Examples include median U-turn, restricted crossing U-turn, and displaced left-turn intersections.
- *Unsignalized intersections,* including two-way STOP-controlled intersections (i.e., intersections where only the side-street approaches are required to stop), all-way STOP-controlled intersections, and roundabouts.
- *Off-street pedestrian and bicycle facilities,* such as bicycle paths or multiuse trails. On-street pedestrian and bicycle facilities are addressed by the methodologies for urban streets and intersections, although not every system element has an associated pedestrian or bicycle methodology.

Performance Measures

The following are key performance measures generated by the HCM for evaluating the operation of motorized vehicles on interrupted-flow roadways:

- *Control delay* is the delay incurred because of the presence of a traffic control device. It includes delay associated with vehicles slowing in advance of an intersection, the time spent stopped on an intersection approach, the time spent as vehicles move through a queue, and the time needed for vehicles to accelerate to their desired speed once through the intersection.
- *Speed* reflects how fast motorists can traverse a roadway section, including the effects of traffic control devices, delays due to turning vehicles at intersections and driveways, and traffic demands on the roadway.
- *Number of stops* reflects how frequently motorists must come to a stop as they travel along an urban street because of traffic control, turning vehicles, midblock pedestrian crossings, and similar factors.
- *Queue length* reflects how far traffic backs up as a result of traffic control (e.g., a queue from a traffic signal) or a vehicle stopped in the travel lane while waiting to make a turn. Queuing is both an important operational measure and a design consideration—queues that are longer than the available storage length can create several types of operational problems. A through-lane queue that extends past the entrance to a turn lane blocks access to the turn lane and keeps it from being used effectively. Similarly, a turn-lane queue overflow into a through lane interferes with the movement of through vehicles. Queues that extend upstream from an intersection can block access into and out of driveways and—in a worst case—can spill back into and block upstream intersections, causing side streets to begin to queue back.
- *Volume-to-capacity (demand-to-capacity) ratios,* whose definition and use are similar to those of uninterrupted-flow roadways.
- *Travel time reliability* measures reflect the consistency (or lack thereof) of travel times or speeds over a long time frame (e.g., a year). As is the case with uninterrupted-flow roadways, reliability measures provide an important contrast to traditional traffic operations performance measures by indicating the range of possible conditions that may occur over a long time frame rather than the average condition during that period.
- The performance measures produced by *traveler perception models* describe how travelers would perceive conditions. These models use a variety of inputs to generate a single performance measure. The measure value predicts the average perception rating that all users of a given mode would give a particular system element. Traveler perception models are frequently applied to pedestrian, bicycle, and transit analyses and are discussed further in Section 3, Quality and Level-of-Service Concepts.
- *Pedestrian space, bicycle speed,* and *number of meeting or passing events* on off-street pedestrian and bicycle facilities can also be of interest to analyses involving the pedestrian and bicycle modes.

MODAL INTERACTIONS

Roadways serve users of many different modes: in particular, motorists, truck operators, pedestrians, bicyclists, and transit passengers. The roadway right-of-way is allocated among the modes through the provision of facilities that ideally serve each mode's needs. However, in many urban situations, the right-of-way is constrained by adjacent land development, which causes transportation engineers and planners to consider trade-offs in allocating the right-of-way. Interactions among the modes that result from different right-of-way allocations are important to consider in analyzing a roadway, and the HCM provides tools for assessing these interactions. Local policies and design standards relating to roadway functional classifications also provide guidance on the allocation of right-of-way; safety and operational concerns should also be addressed. Exhibit 8-1 summarizes some of the key interactions that occur between modes.

Exhibit 8-1
Modal Interaction Summary

Mode Creating the Interaction	Mode Affected by the Interaction: Motorized Vehicle	Pedestrian	Bicycle	Transit
Motorized vehicle	Turning vehicles can delay other vehicles; heavy vehicles (e.g., trucks) have poorer acceleration and deceleration characteristics; traffic signal timing is influenced by relative traffic volumes on intersection approaches; intersection delay tends to increase as automobile volumes increase	Cross-street vehicle volumes influence traffic signal timing (and pedestrian delay); turning movement conflicts between vehicles and pedestrians; automobile and heavy vehicle volumes influence their perceived separation from pedestrians using sidewalks	Automobile and heavy vehicle volumes and speeds, presence of on-street parking, and the degree to which bicyclists are separated from vehicular traffic influence bicyclist comfort; turning movement conflicts with vehicles at intersections	Impacts similar to those of motorized vehicles on other motorized vehicles; buses may be delayed waiting for a gap in traffic when they leave a bus stop; day-to-day variations in traffic volumes and trip-to-trip variations in making or missing green lights affect schedule reliability
Pedestrian	Minimum green times at traffic signals may be dictated by crosswalk lengths; vehicles yield to crossing pedestrians	Cross flows where pedestrian flows intersect cause pedestrians to adjust their course and speed; pedestrian space and comfort decrease as pedestrian volumes increase	Pedestrians being met and passed by bicycles on multiuse paths affect bicyclist comfort because of pedestrians' lower speeds and tendency to walk abreast; on streets, effect on bicycles similar to that on motorized vehicles	Effects similar to those of pedestrians on motorized vehicles; transit riders are often pedestrians before and after their transit trip, so the quality of the pedestrian environment affects the perceived quality of the transit trip
Bicycle	Turning vehicles yield to bicycles; vehicles may be delayed waiting to pass bicycles in shared-lane situations	Bicycles meeting and passing pedestrians on multiuse paths affect pedestrian comfort because of the bicycles' markedly higher speeds	Bicyclists may be delayed when they pass another bicycle on-street; meeting and passing events on off-street pathways affect bicyclist comfort	Effects similar to those of bicyclists on motorized vehicles; bicycles can help extend the area served by a transit stop
Transit	Buses are heavy vehicles; buses stopping in the travel lane to serve passengers can delay other vehicles; transit signal priority measures affect the allocation of green time	Effects similar to those of motorized vehicles on pedestrians, but proportionately greater due to transit vehicles' greater size	Effects similar to those of motorized vehicles on bicyclists, but proportionately greater due to transit vehicles' greater size; transit can help extend the reach of a bicycle trip and allows a trip to be completed in the event of a flat tire or rain	Bus speeds decrease as bus volumes increase; irregular headways increase passenger loads on some buses and increase average wait times for buses

3. QUALITY AND LEVEL-OF-SERVICE CONCEPTS

OVERVIEW

There are many ways to measure the performance of a transportation facility or service—and many points of view that can be considered in making that measurement. The agency operating a roadway, automobile drivers, freight shippers, pedestrians, bicyclists, bus passengers, decision makers, and the community at large all have their own perspectives on how a roadway or service should perform and what constitutes "good" performance. As a result, there is no one right way to measure and interpret performance. The HCM provides a number of tools for describing how well a transportation facility or service operates from a traveler's perspective, a concept termed *quality of service*. One important tool for describing quality of service is the concept of LOS, which facilitates the presentation of results through the use of a familiar A (best) to F (worst) scale. A variety of specific performance measures, termed *service measures*, are used to determine LOS. These three concepts—quality of service, LOS, and service measures—are the topics of this section.

QUALITY OF SERVICE

Quality of service describes how well a transportation facility or service operates from a traveler's perspective.

Quality of service describes how well a transportation facility or service operates from a traveler's perspective. Quality of service can be assessed in a number of ways. Among them are direct observation of factors perceivable by and important to travelers (e.g., speed or delay), surveys of travelers, the tracking of complaints and compliments about roadway conditions, forecasts of traveler satisfaction on the basis of models derived from past traveler surveys, and observation of things not directly perceived by travelers (e.g., average time to clear a crash) affecting things they can perceive (e.g., speed or arrival time at work).

The HCM's focus is on the travel time, travel time reliability, speed, delay, ability to maneuver, and comfort aspects of quality of service. Other aspects of quality of service covered to a lesser degree by the HCM, or covered more thoroughly by its companion documents, include convenience of travel, safety, user cost, availability of facilities and services, roadway aesthetics, and information availability.

Dimensions of system performance and mobility.

Quality of service is one dimension of mobility and overall transportation system performance. Other dimensions to consider are the following (*4*, *5*):

- *Quantity of service*—such as the number of person miles and person-hours provided by the system;
- *Capacity utilization*—including the amount of congestion experienced by users of the system, the physical length of the congested system, and the number of hours that congestion exists; and
- *Accessibility*—for example, the percentage of the populace able to complete a selected trip within a specified time.

LEVEL OF SERVICE

LOS is the stratification of quality of service.

The HCM defines LOS for most combinations of travel mode (i.e., automobile, pedestrian, bicycle, and transit) and roadway system element (e.g., freeway, urban street, intersection) addressed by HCM methodologies. Six levels are defined, ranging from A to F. LOS A represents the best operating conditions from the traveler's perspective and LOS F the worst. For cost, environmental impact, and other reasons, roadways and transit services are not typically designed to provide LOS A conditions during peak periods. Rather, a lower LOS that reflects a balance between individual travelers' desires and society's desires and financial resources is typically the goal. Nevertheless, during low-volume periods of the day, a system element may operate at LOS A.

LOS is used to translate complex numerical performance results into a simple A–F system representative of the travelers' perceptions of the quality of service provided by a facility or service. The LOS letter result hides much of the complexity of facility performance to simplify decision making about whether facility performance is generally acceptable and whether a change in this performance is likely to be perceived as significant by the general public. One of the strengths of the LOS system, and a reason for its widespread adoption by agencies, is its ability to communicate roadway performance to laypersons. However, the system has other strengths and weaknesses, described below, that both analysts and decision makers need to be mindful of.

Step Function Nature of LOS

Defining performance standards on the basis of LOS (or any fixed numerical value) means that small changes in performance can sometimes result in the standard being exceeded when a facility is already operating close to the standard.

The measure of effectiveness for automobiles at traffic signals is the average delay experienced by motorists. As traffic volumes on certain critical approaches increase, so does the average delay. The added delay may or may not result in a change in LOS. An increase of delay of 12 seconds may result in no change in LOS, a drop of one LOS letter, or a drop of two LOS letters, depending on the starting value of delay. Because there are only six possible LOS letters, each covering a range of possible values, the reported LOS does not change until the service measure increases past the threshold value for a given LOS. A change of LOS indicates that roadway performance has transitioned from one given range of traveler-perceivable conditions to another range, while no change in LOS indicates that conditions are in the same performance range as before. The service measure value—in this case, average delay—indicates more specifically where conditions lie within a particular performance range.

Because a small change in a service measure can sometimes result in a letter change in the LOS result, the LOS result may imply a more significant effect than actually occurred. This aspect of LOS can be a particularly sensitive issue when agencies define their performance standards on the basis of LOS, since a small change in performance can trigger the need for potentially costly improvements. However, this issue exists whenever a fixed standard is used, whether or not LOS is the basis of that standard.

Uncertainty and False Precision

Computer software is frequently used to perform traffic operations analyses, and software can report results to many decimal places. However, such precision is often unjustified for five reasons:

1. In contrast to the force of gravity or the flow of water through a pipe, the actions of motorists driving on a roadway can vary. Traffic operations models predict average values of performance measures; the actual value for a measure on a given day may be somewhat higher or lower. Thus, the result reported by every traffic operations model has some uncertainty associated with it.
2. A given traffic operations model may rely on the output of other models that have their own associated result uncertainties.
3. Some model inputs, such as traffic volumes, are taken to be absolute, when there is actually variation in the inputs from month to month, day to day, or even within an hour. Traffic volumes, for example, may vary by 5% to 10% from one weekday to the next.
4. Some HCM models predict traveler perceptions. Two travelers who experience identical conditions may perceive those conditions differently. When many travelers are surveyed, a distribution of responses from "very satisfied" to "very dissatisfied" (or some similar scale) results. The traveler perception models predict the average of those responses.
5. Some alternative tools involve the use of simulation, in which results will vary as inputs are randomly varied within a set distribution and average. Reporting only one result from simulation simplifies the actual results produced.

Therefore, any traffic operations performance measure value, whether resulting from an HCM methodology, simulation, or even field measurement, potentially has a fairly wide range associated with it in which the "true" value actually lies. The LOS concept helps to downplay the implied accuracy of a numeric result by presenting a range of measure results as being reasonably equivalent from a traveler's point of view. However, the same variability issues also mean that the "true" LOS value may be different from the one predicted by a methodology. One way of thinking about a reported value and its corresponding LOS is that they are the statistical "best estimators" of conditions.

LOS Reported Separately by Mode

In an effort to produce a single top-level measure of conditions, some HCM users may be tempted to blend the LOS reported for each mode into a single LOS value for a roadway element. However, each mode's travelers have different perspectives and could experience different conditions while traveling along a particular roadway. The use of a blended LOS carries the risk of overlooking quality-of-service deficiencies for nonautomobile travelers that discourage the use of those modes, particularly if the blended LOS is weighted by the number of modal travelers. Other measures, such as person delay, can be used when an analysis requires a combined measure. The HCM recommends reporting modal LOS results individually.

Neither LOS nor any other single performance measure tells the full story of roadway performance.

Reporting the Big Picture

Analysts and decision makers should always be mindful that neither LOS nor any other single performance measure tells the full story of roadway performance. Depending on the particulars of a given location and analysis, queue lengths, demand-to-capacity ratios, average travel speeds, indicators of safety, and other performance measures may be equally or even more important to consider, regardless of whether they are specifically called out in an agency standard. For this reason, the HCM provides methods for estimating a variety of useful roadway operations performance measures, and not just methods for determining LOS.

SERVICE MEASURES

Service measures are the performance measures that define LOS.

As introduced earlier, service measures are specific performance measures that are used to determine LOS. Exhibit 8-2 summarizes the service measures used by the HCM for different combinations of transportation system elements and travel modes. Some service measures are based on a traveler perception model; the components of each model are given in Exhibit 8-3.

Exhibit 8-2
Service Measures by Individual System Element

	Service Measures			
System Element	**Motorized Vehicle**	**Pedestrian**	**Bicycle**	**Transit**
Freeway facility	Density	--	--	--
Basic freeway segment	Density	--	--	--
Freeway weaving segment	Density	--	--	--
Ramp junction	Density	--	--	--
Multilane highway	Density	--	LOS score[a]	--
Two-lane highway	Percent time-spent-following, speed	--	LOS score[a]	--
Urban street facility	Speed	LOS score[a]	LOS score[a]	LOS score[a]
Urban street segment	Speed	LOS score[a]	LOS score[a]	LOS score[a]
Signalized intersection	Delay	LOS score[a]	LOS score[a]	--
Two-way stop	Delay	Delay	--	--
All-way stop	Delay	--	--	--
Roundabout	Delay	--	--	--
Interchange ramp terminal	Delay	--	--	--
Alternative intersection	Delay	--	--	--
Off-street pedestrian or bicycle facility	--	Space, events[b]	LOS score[a]	--

Notes: [a] See Exhibit 8-3 for the LOS score components.
[b] Events are situations where pedestrians meet bicyclists.

Exhibit 8-3
Components of Traveler Perception Models Used to Generate Service Measures

System Element	Mode	Model Components
Multilane highway and two-lane highway	Bicycle	Perceived separation between bicycles and motor vehicles, pavement quality, automobile and heavy vehicle volume and speed
Urban street facility	Motorized vehicle	Weighted average of segment motorized vehicle LOS scores
	Pedestrian	Urban street segment and signalized intersection pedestrian LOS scores
	Bicycle	Urban street segment and signalized intersection bicycle LOS scores
	Transit	Weighted average of segment transit LOS scores
Urban street segment	Motorized vehicle	Stops per mile, left-turn lane presence
	Pedestrian	Pedestrian density, sidewalk width, perceived separation between pedestrians and motor vehicles, motor vehicle volume and speed, midblock crossing difficulty
	Bicycle	Perceived separation between bicycles and motor vehicles, pavement quality, automobile and heavy vehicle volume and speed, driveway conflicts
	Transit	Service frequency, perceived speed, pedestrian LOS
Signalized intersection	Pedestrian	Street crossing delay, pedestrian exposure to turning vehicle conflicts, crossing distance
	Bicycle	Perceived separation between bicycles and motor vehicles, crossing distance
Off-street pedestrian or bicycle facility	Bicycle	Average meetings/minute, active passings/minute, path width, centerline presence, delayed passings

Note: The motorized vehicle traveler perception model for urban street segments and facilities is not used to determine LOS; however, it is provided as a performance measure to facilitate multimodal analyses.

4. ANALYSIS PROCESS

LEVELS OF HCM ANALYSIS

The HCM can be applied at the *operational, planning and preliminary engineering,* and *design* analysis levels. The required input data typically remain the same at each analysis level, but the degree to which default values are used instead of measured or forecast values differs. In addition, operational and planning and preliminary engineering analyses frequently evaluate the LOS that will result from a given set of inputs, while design analyses evaluate the facility characteristics that will be needed to achieve a desired LOS.

Operational Analysis

In an operational analysis, an analyst applies an HCM methodology directly and supplies all of the required input parameters from measured or forecast values. No, or minimal, default values are used. Of the available ways to apply HCM methodologies, operational analyses provide the highest level of accuracy but, as a result, also require the most detailed data collection, which has time and cost implications.

An operational analysis helps in making decisions about operating conditions. Typical alternatives consider, for example, changes in traffic signal timing and phasing, changes in lane configurations, spacing and location of bus stops, the frequency of bus service, or the addition of a bicycle lane. The analysis produces operational measures that can be used to compare the alternatives.

As discussed earlier in this chapter, even though a model's results may be highly accurate, any variability associated with the model's inputs can affect the model's results.

Planning and Preliminary Engineering Analysis

In planning and preliminary engineering analyses, an analyst applies an HCM methodology by using default values for some to nearly all of the model inputs—for example, through the use of generalized service volume tables. The results are less accurate than those of an operations analysis, but the use of default values reduces the amount of data collection and the time required to perform an analysis. In a large-scale planning study, where a large number of roadways may be evaluated, this level of analysis may be the best practical, given time and budget constraints. For future-focused studies, not all of the model inputs may be known or forecastable, which suggests the need for a planning analysis with the use of default values for the unknown model inputs.

Planning analyses are applications of the HCM generally directed toward broad issues such as initial problem identification (e.g., screening a large number of locations for potential operations deficiencies), long-range analyses, and statewide performance monitoring. An analyst often must estimate the future times at which the transportation system will fall below a desired LOS. Preliminary engineering analyses are often conducted to support planning decisions related to a roadway design concept and scope and in performing alternatives analyses (*5*). These studies can also assess proposed systemic policies, such as lane use control for heavy vehicles, systemwide freeway ramp metering and other intelligent transportation systems applications, and the use of demand management techniques such as congestion pricing.

Generalized Service Volume Tables

Generalized service volume tables are sometimes used in planning analyses. These tables are constructed by applying default values to an HCM methodology and then incrementally determining the maximum number of vehicles that a roadway could carry at a given LOS under the assumed conditions.

Service volume results should be applied with care, since actual conditions will likely vary in some way from the assumptions used to develop the table.

The use of a service volume table is most appropriate in situations in which evaluating every roadway or intersection within a study area is not practical. Examples of these applications would be city, county, or statewide planning studies, where the size of the study area makes conduct of a capacity or LOS analysis for every roadway segment infeasible. For these types of planning applications, the focus of the effort is simply to highlight potential problem areas (for example, locations where demand may exceed capacity or where a desired LOS may be exceeded). For such applications, a service volume table can be a useful screening tool. Once potential problem areas have been identified, more detailed analyses can be performed for those locations.

The HCM provides generalized service volume tables for

- *Freeway facilities*
- *Multilane highways*
- *Two-lane highways*
- *Urban street facilities*
- *Signalized intersections*

The characteristics of any given roadway will likely vary in some way from the assumed input values used to develop a service volume table. Therefore, the results from a service volume table should be treated as rough approximations. Service volume tables should not be substituted for other tools to make a final determination of the operational adequacy of a particular roadway.

Design Analysis

Design analyses typically apply the HCM to establish the detailed physical features that will allow a new or modified roadway to operate at a desired LOS. Design projects are usually targeted for mid- to long-term implementation. Not all the physical features that a designer must determine are reflected in the HCM models. Typically, analysts using the HCM are seeking to determine such elements as the basic number of lanes required and the need for auxiliary or turning lanes. However, an analyst can also use the HCM to establish values for elements such as lane width, steepness of grade, the length of added lanes, the size of pedestrian queuing areas, the widths of sidewalks and walkways, and the presence of bus pullouts.

The data required for design analyses are detailed and are based substantially on proposed design attributes. However, the intermediate- to long-term focus of the work will require the use of some default values. This simplification is justified in part by the limits on the accuracy and precision of the traffic forecasts with which the analyst will be working.

ANALYSIS TOOL SELECTION

Types of Tools

Each analytical or simulation tool, depending on the application, has its own strengths and weaknesses. It is important to relate relevant modeling features to the needs of the analysis and to determine which tool satisfies these needs to the greatest extent.

HCM methodologies are *deterministic* and *macroscopic*. A deterministic model will always produce the same result for a given set of inputs. A macroscopic model considers average conditions experienced by vehicles over a period of time (typically 15 minutes or 1 hour). In contrast, microsimulation models are *stochastic* and *microscopic*. In a stochastic model, a different random number seed will produce a different modeling result; therefore, the outcome from a simulation run based on a stochastic model cannot be predicted with certainty before the analysis begins. Microscopic models simulate the movement of individual vehicles on the basis of car-following and lane-changing theories.

Situations When Alternative Tools Might Be Considered

The HCM is the product of a large number of peer-reviewed research projects and reflects the best available techniques (at the time of publication) for determining capacity and LOS. However, the research behind the HCM has not addressed every possible situation that can arise in the real world. Therefore, the HCM documents the limitations of its procedures and highlights situations when alternative analysis tools should be considered to supplement or substitute for the HCM. The following are examples of these situations:

- The configuration of the facility has elements that are beyond the scope of the HCM procedures. Each HCM procedural chapter identifies the specific limitations of its own methodology.
- Viable alternatives being considered in the study require the application of an alternative tool to make a more informed decision.
- The performance measures are compatible with corresponding HCM measures and the decision process requires additional performance measures, such as fuel consumption and emissions, that are beyond the scope of the HCM.
- The system under study involves a group of different facilities with interactions that require the use of more than one HCM chapter. Alternative tools can analyze these facilities as a single system.
- Routing is an essential part of the problem being addressed.
- The quantity of input or output data required presents an intractable problem for the HCM procedures.
- The HCM procedures predict overcapacity conditions that last throughout a substantial part of a peak period or queues that overflow the available storage space.

The Federal Highway Administration's *Traffic Analysis Toolbox* (6) provides general guidance on the use of traffic analysis tools, including the HCM. More detailed guidance for alternative tool application to specific system elements is presented in Volumes 2 and 3 of the HCM. Supplemental examples involving situations beyond the scope of the HCM procedures are presented in Volume 4.

INTERPRETING RESULTS

Uncertainty and Variability

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 size of the range, and therefore the degree of uncertainty, is a function of several variables, including the quality of the input data, the inherent variability of the model, and the degree to which the model accounts for all of the factors that may affect the results. The uncertainty may be amplified by imperfect knowledge of the traveler perception aspects of quality of service.

When simulation tools are applied, uncertainty is normally addressed by performing multiple simulation runs that use different random number seeding. Regardless of the modeling approach, a sensitivity analysis may be performed to assess the degree to which input data variation is likely to affect the range of performance results. Depending on the particular model and the specifics of the situation being modeled, small changes in model inputs can have large impacts on model outputs.

Accuracy and Precision

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. In most cases, accuracy of the field data on which the analyses are based (e.g., traffic volumes) to within 5% or 10% of the true value is the best that can be anticipated. Thus, extreme accuracy cannot be expected from the computations performed with these inputs, and the final results must be considered as estimates that are accurate and precise only within the limits of the inputs used.

Comparing HCM Results with Alternative Tools

The exact definitions of performance measures are an important issue, particularly when performance measures produced by different analysis tools are to be compared. Many tools produce performance measures with the same name (e.g., "delay"), but the definitions and methods of computation can differ widely. Chapter 7, Interpreting HCM and Alternative Tool Results, presents general guidance on comparing results. The chapters in HCM Volumes 2 and 3 present guidance on this topic for specific roadway elements.

Another source of difference in the performance measures obtained from different tools lies in their treatment of incomplete trips. Incomplete trips include those that enter a facility during a given analysis period (e.g., a 15-minute period) and exit during a subsequent period, and those that exit a facility after entering in a previous analysis period. To overcome differences among analysis tools, inclusion of an uncongested interval at all time and space boundaries of the analysis period is important.

When undercapacity operation is being studied, the definition of the facility in time and space is less important. The facility's operation tends to be more homogeneous when demand is less than capacity. For most performance measures, extending the analysis period will give a larger sample of vehicles but will not affect the performance measures significantly.

PRESENTING RESULTS

Tabular values and calculated results are displayed in a consistent manner throughout the HCM. It is suggested that analysts applying the HCM adhere to these conventions. A key objective is to present results in a way that indicates to users, decision makers, and other viewers the level of precision and accuracy associated with the results. This may require rounding results or presenting an appropriate number of digits after the decimal point, consistent with a result's expected precision and accuracy.

5. DECISION-MAKING CONSIDERATIONS

The HCM provides procedures for capacity and quality-of-service analyses and therefore serves as an analytical tool for transportation engineers and planners. However, the HCM is only a guidance document: it does not endeavor to establish a legal standard for highway design or construction. This section describes the role of other guidance and standards documents that complement the HCM, along with issues for decision makers to consider should they choose to adopt HCM service measures as standards.

ROLE OF HCM COMPANION DOCUMENTS

Throughout its history, the HCM has been a fundamental reference work for transportation engineers and planners. However, it is but one of a number of documents that play a role in the planning, design, and operation of transportation facilities and services. The HCM's scope is to provide tools to evaluate the performance of highway and street facilities in terms of operational and traveler perception measures. This section describes companion documents to the HCM that cover important topics outside the HCM's scope.

Highway Safety Manual

The *Highway Safety Manual* (HSM) (*7*) provides analytical tools and techniques for quantifying the safety effects of decisions related to planning, design, operations, and maintenance. The information in the HSM is provided to assist agencies as they integrate safety into their decision-making processes. It is a nationally used resource document intended to help transportation professionals conduct safety analyses in a technically sound and consistent manner, thereby improving decisions made on the basis of safety performance.

A Policy on Geometric Design of Highways and Streets

The American Association of State Highway and Transportation Officials' (AASHTO's) *A Policy on Geometric Design of Highways and Streets* ("Green Book") (*8*) provides design guidelines for roadways ranging from local streets to freeways, in both urban and rural locations. The guidelines "are intended to provide operational efficiency, comfort, safety, and convenience for the motorist," while also emphasizing the need to consider the use of roadway facilities by other modes.

Manual on Uniform Traffic Control Devices

The Federal Highway Administration's *Manual on Uniform Traffic Control Devices for Streets and Highways* (MUTCD) (*9*) is the national standard for traffic control devices for any street, highway, or bicycle trail open to public travel. Of particular interest to HCM users are the sections of the MUTCD pertaining to warrants for all-way STOP control and traffic signal control, signing and markings to designate lanes at intersections, and associated considerations of adequate roadway capacity and less restrictive intersection treatments.

Transit Capacity and Quality of Service Manual

The *Transit Capacity and Quality of Service Manual* (TCQSM) (*10*) is the transit counterpart to the HCM. The TCQSM contains information on the various types of public transportation and their capacities and provides a framework for measuring transit service from the passenger point of view.

Traffic Analysis Toolbox

At the time of writing, the Federal Highway Administration had produced 14 volumes of the *Traffic Analysis Toolbox* (*6*), providing guidance on the selection and deployment of a range of traffic analysis tools, including the HCM.

USE OF THE HCM IN DECISION MAKING

Although the HCM does not set standards—for example, it does not specify a particular LOS that should be provided for a particular roadway type—it is referenced in the AASHTO Green Book (*8*), and numerous agencies and jurisdictions have adopted LOS standards based on the HCM. This section discusses issues that agencies and jurisdictions should consider when they apply HCM methods, set operations standards based on the HCM, or both.

Impact of Changes in HCM Methods

Each new edition of the HCM incorporates new methodologies and—in some cases—new service measures for evaluating roadway system elements. This edition of the HCM is no different. Sometimes, new methods are added to address emerging types of system elements (e.g., roundabouts, managed lanes, alternative intersections), to assess roadway performance in new ways (e.g., travel time reliability), or to address new paradigms (e.g., designing and operating roadways to serve multiple travel modes). In other cases, methods are updated to improve estimates of service and other performance measures. These changes can affect transportation agencies that apply the HCM:

- *New methods* provide additional tools for transportation agencies to use in planning and operating their roadway network.
- *Changes in methodologies* are designed to provide better estimates of performance than the previous version of the method, on the basis of new research. Because the underlying methodology has changed, the estimated performance of a roadway can change as a result of applying the new method, even though nothing about the roadway itself has changed. These changes can result in the need for new projects to address the newly identified deficiencies, as well as the possibility that previously identified projects are no longer needed.
- *Changes in service measures or LOS thresholds* are intended to reflect more closely the traveler's perspective of roadway operations. In these cases, agencies that have adopted operations standards using such measures are encouraged to reconsider their standards to ensure that they still represent the quality of service the agency wishes to provide. These kinds of changes in the HCM may also have planning and project programming implications, since the need for or scale of a given project may change.

- *Changes in HCM default values* may cause analysis results to differ from one version of the HCM to the next, since some of the input data provided to a method have changed even though the underlying method has not. Following the HCM's recommendations of using field-measured input values whenever possible and locally generated default values otherwise avoids this issue.

Incorporating HCM Analysis Results into Decision Making

Agencies and jurisdictions adopt roadway design and operations standards for a number of reasons, including consistency in roadway design across a jurisdiction and provision of an objective basis for making decisions on required improvements. As mentioned earlier, numerous agencies and jurisdictions have chosen to adopt LOS standards for their roadways. The existence of computerized tools that implement HCM procedures makes it easy for analysts to test a number of roadway improvements against a LOS standard. However, the analysis does not end once a LOS result has been determined.

The existence of a LOS F condition does not, by itself, indicate that action must be taken to correct the condition. Conversely, meeting a LOS standard does not necessarily mean that no problem exists or that an improvement that produces the desired LOS is a desirable solution. Other issues, including but not limited to safety, impacts on other modes, traffic signal warrants, turn-lane warrants, cost–benefit issues, and access management, may also need to be considered as part of the analysis, recommendations, and eventual decision. As always, engineering judgment should be applied to any recommendations resulting from HCM (or alternative tool) analyses.

Two examples of common situations where a LOS result considered by itself might lead to a decision different from one that would be reached if other factors were also considered are given below.

Traffic Signal Warrants

The MUTCD (*9*) provides a number of warrants that indicate when a traffic signal may be justified. It is possible to have a condition at a two-way STOP intersection—particularly when a low-volume minor street intersects a high-volume major street—where the minor street approach operates at LOS F but does not meet traffic signal warrants. Because the MUTCD is the standard for determining when a traffic signal is warranted, a LOS F condition by itself is not sufficient justification for installing a signal.

Turn-Lane Warrants

A number of agencies and jurisdictions have adopted warrants that indicate when the installation of turn lanes may be justified at an intersection. It is possible for an HCM analysis to indicate that the addition of a turn lane will result in an acceptable LOS but for the turn-lane warrant analysis to determine that the necessary conditions for installing a turn lane have not been satisfied. In this case, the potential for a satisfactory LOS in the future would not be sufficient justification by itself for installing the turn lane.

6. REFERENCES

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CHAPTER 9
GLOSSARY AND SYMBOLS

CONTENTS

1. GLOSSARY

Chapter 9, Glossary and Symbols, defines the terms used in the *Highway Capacity Manual* (HCM) and presents the symbols used in the manual's equations. Highway transportation terminology has evolved over time to create multiple definitions, and the confusion has been compounded by technical jargon. The definitions, abbreviations, and symbols presented here are intended to establish a consistent terminology for use in the HCM. It is recognized that other definitions and usage could exist.

A

Acceleration/deceleration delay – Delay experienced by vehicles slowing from and subsequently returning to their running speed.

Acceleration lane – A paved noncontinuous lane, including tapered areas, allowing vehicles to accelerate when they enter the through-traffic lane of the roadway.

Access point – An unsignalized intersection, driveway, or opening on either side of a roadway. See also *active access point*.

Access point density – The total number of access points on both sides of the roadway, divided by the length of the segment.

Accessibility – The percentage of the populace able to complete a selected trip within a specified time.

Accuracy – The degree of an estimate's agreement with a standard or true value.

Active access point – An access point whose volume is sufficient to affect segment operations during the analysis period; as a rule of thumb, an access point approach is considered active if it has an entering flow rate of 10 veh/h or more during the analysis period.

Active bottleneck – A segment with a demand-to-capacity ratio greater than 1.0, an actual flow-to-capacity ratio equal to 1.0, and queuing upstream of the bottleneck segment.

Active passings – The number of other path users traveling in the same direction as the average bicyclist who are passed by that bicyclist.

Active traffic and demand management (ATDM) – The dynamic management, control, and influence of travel demand, traffic demand, and traffic flow on transportation facilities.

Actuated control – A defined phase sequence in which the presentation of each phase depends on whether the phase is on recall or the associated traffic movement has submitted a call for service through a detector.

Actuation – A detection of a roadway user that is forwarded to the controller by a detector.

Adaptive control – Second-by-second optimization of signal timings according to the current monitor information and the priorities assigned to each vehicle and pedestrian type by the operating agency.

Adjacent friction effect – A speed reduction that occurs in a single managed lane without barrier separation when densities in the adjacent general purpose lane are relatively high.

Adjusted saturation flow rate – See *saturation flow rate, adjusted*.

Adjustment – An additive or subtractive quantity that adjusts a parameter for a base condition to represent a prevailing condition.

Adjustment factor – A factor that adjusts a parameter for a base condition to represent a prevailing condition.

Aggregate delay – The summation of delays for multiple lanes or lane groups, usually aggregated for an approach, an intersection, or an arterial route.

Algorithm – A set of rules for solving a problem in a finite number of steps.

All-way STOP-controlled (AWSC) intersection – An intersection with STOP signs on all approaches. The driver's decision to proceed is based on a consensus of right-of-way governed by the traffic conditions of the other approaches and the rules of the road (e.g., the driver on the right has the right-of-way if two vehicles arrive simultaneously).

Alternative dataset – An HCM dataset that describes changes in base conditions (e.g., demand, traffic control, available lanes) associated with a work zone or special event, along with the times when the alternative dataset is in effect.

Alternative intersection – An intersection created by rerouting one or more movements (often left turns) from their usual places to secondary junctions.

Alternative tool – An analysis procedure outside of the HCM that may be used to compute measures of transportation system performance for analysis and decision support.

Analysis hour – A single hour for which a capacity analysis is performed on a system element.

Analysis period – The time interval evaluated by a single application of an HCM methodology, typically 15 min.

Analytical model – A model based on traffic flow theory, combined with the use of field measures of driver behavior, resulting in an analytic formulation of the relationship between the field measures and performance measures such as capacity and delay.

Annual average daily traffic (AADT) – The total volume of traffic passing a point or segment of a highway facility in both directions for 1 year divided by the number of days in the year.

Approach – A set of lanes at an intersection that accommodates all left-turn, through, and right-turn movements from a given direction.

Approach delay – The control delay for a given approach.

Approach grade – The average grade along the approach, as measured from the stop line to a point 100 ft upstream of the stop line along a line parallel to the direction of travel. An uphill condition has a positive grade, and a downhill condition has a negative grade.

Area – An interconnected set of transportation facilities serving movements within a specified geographic space, as well as movements to and from adjoining areas.

Area type – A description of the environment in which a system element is located.

Arrival–departure polygon – A graphic tool for computing the number of full stops.

Arrival rate – The mean of the statistical distribution of vehicles arriving at a point or uniform segment of a lane or roadway.

Arrival type – Six assigned categories for the quality of progression for a given approach to a signalized intersection.

Arterial street – A street interrupted by traffic control devices (e.g., signals, STOP signs, or YIELD signs) that primarily serves through traffic and that secondarily provides access to abutting properties. See also *urban street.*

ATDM – See *active traffic and demand management.*

At grade – At ground level.

Automobile – A two-axle, four-wheeled vehicle.

Automobile mode – A submode of the motorized vehicle mode in which an automobile is used on a roadway.

Automobile traveler perception score – A numerical output from a traveler perception model that indicates the average rating that automobile travelers would give an urban street under a given set of conditions.

Autonomous vehicle – A partially or fully self-driving vehicle.

Auxiliary lane – See *freeway auxiliary lane.*

Available time-space – The product of available time and available space for pedestrian circulation on a crosswalk at a signalized intersection.

Average bicyclist – A bicyclist traveling at the average speed of all bicycles.

Average running speed – The length of a segment divided by the average running time of vehicles that traverse the segment.

Average spot speed – See *time mean speed.*

Average travel speed – The length of the highway segment divided by the average travel time of all vehicles traversing the segment, including all stopped delay times. Equal to *space mean speed.*

B

Back of queue – The maximum backward extent of queued vehicles during a typical cycle, as measured from the stop line to the last queued vehicle.

Barrier – **1.** A reference point in the cycle at which one phase in each ring must reach a common point of termination, to ensure that there will be no concurrent selection and timing of conflicting movements in different rings. **2.** A physical object or pavement marking designed to prevent vehicles from entering or departing a section of roadway.

Barrier 1 managed lane segment – A single managed lane separated from the adjacent general purpose lane by a physical object; movements between the managed and general purpose lanes take place at designated locations.

Barrier 2 managed lane segment – Multiple managed lanes separated from the adjacent general purpose lane by a physical object; movements between the managed and general purpose lanes take place at designated locations.

Barrier pair – A pair of phases within the same ring and barrier that cannot be displayed concurrently.

Base capacity – The flow rate achievable under base conditions. Base capacity reflects ideal conditions on a facility with no capacity-reducing effects.

Base conditions – A set of specified standard conditions (e.g., good weather, good and dry pavement conditions, familiar users, no impediments to traffic flow) that must be adjusted to account for prevailing conditions that do not match.

Base dataset – An HCM dataset that describes base conditions (particularly demand and factors influencing capacity and free-flow speed) when work zones and special events are not present.

Base free-flow speed – The potential free-flow speed based only on the highway's horizontal and vertical alignment, not including the impacts of lane widths, lateral clearances, median type, and access points.

Base length – The distance between the points in a weaving segment where the edges of the travel lanes of the merging and diverging roadways converge.

Base saturation flow rate – See *saturation flow rate, base.*

Base scenario – See *scenario, base.*

Baseline uniform delay – The average uniform delay when there is no initial queue.

Basic freeway segment – A length of freeway facility whose undersaturated operations are unaffected by weaving, diverging, or merging.

Bicycle – A vehicle with two wheels tandem, propelled by human power, and usually ridden by one person.

Bicycle, electric – A vehicle with two wheels tandem, propelled by an electric motor that does not require pedaling effort to engage.

Bicycle, electric assist – A vehicle with two wheels tandem, with an electric motor that boosts human pedaling effort up to a designated motor-assisted top speed.

Bicycle facility – A road, path, or way specifically designated for bicycle travel, whether exclusively or with other vehicles or pedestrians.

Bicycle lane – A portion of a roadway designated by striping, signing, and pavement markings for the preferential or exclusive use of bicycles.

Bicycle LOS score – see *level-of-service score.*

Bicycle mode – A travel mode under which a nonmotorized bicycle is used on a roadway or pathway.

Bicycle path – A bikeway physically separated from motorized traffic by an open space or barrier, either within the highway right-of-way or within an independent right-of-way.

Boarding island – A raised area within the roadway that allows buses to stop to serve passengers from an inside lane.

Boarding lost time – Time spent waiting for passengers to travel from their waiting position at the bus stop to the bus door.

Body ellipse – The practical minimum area for standing pedestrians.

Bottleneck – A system element on which demand exceeds capacity.

Boundary intersection – An intersection defining the endpoint of an urban street segment.

Breakdown – **1.** The transition from noncongested to congested conditions typically observed as a speed drop accompanied by queue formation. **2.** A sudden drop in speed of at least 25% below the free-flow speed for a sustained period of at least 15 min that results in queuing upstream of the bottleneck.

Breakdown flow – The flow at which operations transition from noncongested to congested.

Buffer 1 managed lane segment – A single managed lane separated from the adjacent general purpose lane by a painted buffer; movements between the managed and general purpose lanes take place at designated locations.

Buffer 2 managed lane segment – Multiple managed lanes separated from the adjacent general purpose lane by a painted buffer; movements between the managed and general purpose lanes take place at designated locations.

Buffer width – The distance between the outside edge of the paved roadway (or face of curb, if present) and the near edge of the sidewalk.

Buffered bicycle lane – A bicycle lane paired with a designated space buffering it from parked or moving motor vehicles.

Bus – A self-propelled, rubber-tired road vehicle designed to carry a substantial number of passengers (at least 16) and commonly operated on streets and highways.

Bus lane – See *exclusive bus lane.*

Bus mode – A transit mode operated by rubber-tired vehicles that follow fixed routes and schedules along roadways.

Bus shelter – See *shelter.*

Bus stop – A designated area along a street where one or more buses can simultaneously stop to load and unload passengers.

Bus stop failure – A condition that occurs when a bus arriving at a stop finds all loading areas occupied and must wait for space to become available.

Bypass lane – A lane provided at a roundabout that allows a particular traffic movement to avoid using the circulatory roadway.

C

Calibration – The process by which the analyst selects the model parameters that result in the best reproduction of field-measured local traffic conditions by the model.

Call – A request for service by vehicles or pedestrians to a controller.

Capacity – The maximum sustainable hourly flow rate at which persons or vehicles reasonably can be expected to traverse a point or a uniform section of a lane or roadway during a given time period under prevailing roadway, environmental, traffic, and control conditions.

Capacity adjustment factor – An adjustment to base capacity to reflect the effects of severe weather, incidents, and work zones. It can also be used to calibrate the freeway facility model to reflect local conditions.

Capacity drop phenomenon – See *queue discharge capacity drop.*

Case – See *degree-of-conflict case.*

C-D roadway – See *collector–distributor roadway.*

Centerline – On a shared-use path, a paint stripe separating opposing directions of path users.

Central area pricing – An areawide implementation of congestion pricing that imposes tolls for vehicles entering a central area street network during certain hours of certain days.

Central business district (CBD) – An area with characteristics including narrow street rights-of-way, frequent parking maneuvers, vehicle blockages, taxi and bus activity, small-radius turns, limited use of exclusive turn lanes, high pedestrian activity, dense population, and midblock curb cuts.

Change interval – See *yellow change interval.*

Change period – The sum of the yellow change interval and red clearance interval for a given phase.

Circulating flow – The flow conflicting with the entry flow on the subject approach to a roundabout (i.e., the flow passing in front of the splitter island next to the subject entry).

Circulation area – **1.** The portion of a sidewalk intended to be used for pedestrian movement. **2.** The average area available to each person using a pedestrian facility.

Circulation time-space – The total available time-space minus the time-space occupied by pedestrians waiting to cross a crosswalk.

Circulatory roadway – The continuous-flow section of a roundabout that requires other vehicles entering the roadway to yield.

Class I two-lane highways – Highways where motorists expect to travel at relatively high speeds, such as major intercity routes, primary connectors of major traffic generators, daily commuter routes, or major links in state or national highway networks.

Class II two-lane highways – Highways where motorists do not necessarily expect to travel at high speeds, such as access routes to Class I facilities, scenic or recreational routes, or routes passing through rugged terrain.

Class III two-lane highways – Highways serving moderately developed areas, such as portions of a Class I or Class II highway that pass through small towns or developed recreational areas.

Clearance interval – See *red clearance interval.*

Clearance lost time – The latter part of the change period that is not typically used by drivers to proceed through the intersection (i.e., they use this time to stop in advance of the stop line).

Clearance time – **1.** The interval after a bus is ready to depart during which a loading area is not available for use by a following bus, consisting of the sum of reentry delay and the time for a bus to start up and travel its own length, clearing the stop. **2.** See *clearance lost time* and *red clearance interval.*

Climbing lane – A lane added on an upgrade on a two-lane highway to allow traffic to pass heavy vehicles whose speeds are reduced.

Cloverleaf interchange – An interchange with four loop ramps and four diagonal ramps, with no traffic control on either crossing roadway.

Collector street – A surface street providing land access and traffic circulation within residential, commercial, and industrial areas.

Collector–distributor roadway (C-D roadway) – A continuous roadway without local access provided parallel to a freeway mainline through one or more interchanges for the purpose of removing weaving movements or closely spaced merges and diverges from the mainline.

Common green time – The period of time when the phases at the two intersections of an interchange both provide a green indication to a particular origin–destination movement.

Complete trip – A vehicle that enters the spatial domain of an analysis during the analysis period and is able to exit the domain successfully before the end of the analysis period.

Composite grade – A series of adjacent grades along a highway that cumulatively has a more severe effect on operations than each grade separately.

Compressed diamond interchange – A diamond interchange with a separation of 400 to 800 ft between the two intersections.

Computational engine – A software implementation of one or more models.

Concurrency groups – Phase pairs that can operate concurrently with each other.

Conflict – The crossing, merging, or diverging of two traffic movements at an intersection.

Conflicting approach – At an all-way STOP-controlled intersection, an approach to the left or right of the subject approach.

Conflicting flow rate – The total flow rate in conflict with a specific movement at an unsignalized intersection.

Conflicting movements – Vehicular, pedestrian, or bicycle streams that seek to occupy the same space at the same time.

Congestion – **1.** A traffic operation condition that arises when demand approaches or exceeds a system element's capacity and that is characterized by high vehicular density and vehicle speeds that are lower than the desired speeds. **2.** A difference between highway system performance in terms of travel time expected by users and actual system performance—for example, an intersection that may appear congested in a rural community may not even register as an annoyance in a large metropolitan area. See also *recurring congestion* and *nonrecurring congestion*.

Congestion pricing – The practice of charging tolls for use of all or part of a facility or a central area according to the expected or actual severity of congestion.

Connected vehicle – A vehicle with the capability of identifying threats and hazards on the roadway and communicating this information over wireless networks to other vehicles as well as the traffic management center to give drivers alerts and warnings.

Continuous access managed lane segment – A single managed lane where vehicles can move between the managed and adjacent general purpose lane at any point within the segment.

Continuous-flow intersection – See *displaced left-turn intersection*.

Control – **1.** The driver's interaction with the vehicle in terms of speed and direction (accelerating, braking, and steering). **2.** The use of signs, signals, markings, and other devices to regulate, warn, and guide drivers.

Control condition – The traffic controls and regulations in effect for a segment of street or highway, including the type, phasing, and timing of traffic signals; STOP signs; lane use and turn controls; and similar measures.

Control delay – Delay brought about by the presence of a traffic control device, including delay associated with vehicles slowing in advance of an intersection, the time spent stopped on an intersection approach, the time spent as vehicles move up in the queue, and the time needed for vehicles to accelerate to their desired speed.

Controlled – Having a traffic control device that interrupts traffic flow (e.g., a traffic signal, STOP sign, or YIELD sign).

Controller – The piece of hardware that determines how a traffic signal responds to calls based on signal timing parameters.

Conventional diamond interchange – A diamond interchange with a separation of 800 ft or more between the two intersections.

Coordinated actuated control – A variation of semiactuated control that uses the controller's force-off settings to constrain the noncoordinated phases associated with the minor movements such that the coordinated phases are served at the appropriate time during the signal cycle and progression for the major movements is maintained.

Coordination – The ability to synchronize multiple intersections to enhance the operation of one or more directional movements in a system.

Corridor – A set of parallel transportation facilities designed to move people between two locations, for example, a freeway and an arterial street.

Crawl speed – **1.** The maximum sustained speed that can be maintained by a specified type of vehicle on a constant upgrade of a given percent. **2.** The speed at which trucks descend a steep downgrade when they operate in a low gear to apply engine braking.

Critical density – The density at which capacity occurs for a given facility.

Critical headway – The minimum headway in the major traffic stream that will allow the entry of one minor-street vehicle.

Critical lane groups – The lane groups that have the highest flow ratio for a given signal phase.

Critical phase – One phase of a set of phases that occur in sequence and whose combined flow ratio is the largest for the signal cycle.

Critical platoon flow rate – The minimum flow rate associated with platoon headways that are too short to be entered (or crossed) by minor movements.

Critical segment – The segment that will break down first, given that all traffic, roadway, and control conditions do not change, including the spatial distribution of demands on each component segment.

Critical speed – The speed at which capacity occurs for a segment.

Critical volume-to-capacity ratio – The proportion of available intersection capacity used by vehicles in critical lane groups.

Cross flow – A pedestrian flow that is approximately perpendicular to and crosses another pedestrian stream (e.g., where two walkways intersect or at a building entrance); in general, the lesser of the two flows is referred to as the cross-flow condition.

Cross weave – A condition that occurs when traffic from a general purpose on-ramp must cross multiple general purpose lanes to access the managed lane at a nearby ramp or access segment, or when traffic from a managed lane must cross multiple general purpose lanes to access a general purpose off-ramp.

Crossing time – The curb-to-curb crossing distance divided by the pedestrian walking speed specified in the *Manual on Uniform Traffic Control Devices.*

Crossover – A section of a freeway work zone where traffic in one direction is shifted across the median on a temporary roadway to or from the (normally) opposite-direction roadway, which is temporarily used in two-directional operation.

Crosswalk – See *pedestrian crosswalk.*

Crosswalk occupancy time – The product of the pedestrian service time and the number of pedestrians using a crosswalk during one signal cycle.

Cumulative distribution function – A function giving the number or percent of all observations in the travel time distribution at or below a specified travel time bin.

Curb extension – An extension of the sidewalk to the edge of the travel or bicycle lane.

Cycle – A complete sequence of signal indications.

Cycle failure – A condition where one or more queued vehicles are not able to depart an intersection as a result of insufficient capacity during the cycle in which they arrive.

Cycle length – **1.** The total time for a signal to complete one cycle. **2.** For a work zone involving alternating one-way operation, the average time taken to serve each direction of travel once.

Cycle lost time – The time lost during the cycle. It represents the sum of the lost time for each critical phase.

Cyclic spillback – Queue spillback that occurs when the queue from a signalized intersection extends back into an upstream intersection during a portion of each signal cycle and then subsides.

D

Daily service volume – The maximum total daily volume in both directions that can be sustained in a given segment without violating the criteria for a given LOS in the peak direction in the worst 15 min of the peak hour under prevailing roadway, traffic, and control conditions.

Dallas phasing – A phasing option that allows the left-turn movements to operate in the protected–permitted mode without causing a "yellow trap" safety concern. It effectively ties the left turn's permitted-period signal indication to the opposing through movement signal indication. It is also used with a flashing yellow arrow left-turn signal display.

Deceleration delay – See *acceleration/deceleration delay.*

Deceleration lane – A paved noncontinuous lane, including tapered areas, allowing vehicles leaving the through-traffic lane of the roadway to decelerate.

De facto lane – A lane designated for multiple movements but that may operate as an exclusive lane because of a dominant movement demand.

Default value – A representative value entered into a model that may be appropriate in the absence of local data.

Degree-of-conflict case – For all-way STOP-controlled intersections, a particular combination of vehicle presence on other approaches with respect to the subject approach.

Degree of saturation – See *demand-to-capacity ratio.*

Degree of utilization – The product of the arrival rate and the mean departure headway.

Delay – Additional travel time experienced by a driver, passenger, bicyclist, or pedestrian beyond that required to travel at the desired speed. See also specific types of delay (e.g., *control delay, queue delay*).

Delay due to environmental conditions – Additional travel time experienced due to severe weather conditions.

Delayed crossing – A condition under which a pedestrian is unable to cross immediately on reaching an unsignalized crossing.

Delayed passing maneuver – The inability of an average bicyclist to make a passing maneuver immediately due to the presence of both another path user ahead of the overtaking average bicyclist in the subject direction and a path user in the opposing direction.

Demand – The number of vehicles or other roadway users desiring to use a given system element during a specific time period, typically 1 h or 15 min.

Demand adjustment factor – An adjustment to base demand to reflect the effects of severe weather, incidents, and work zones. It can also be used to calibrate the freeway facility model.

Demand flow rate – The count of vehicles arriving at the system element during the analysis period, converted to an hourly rate. When this flow rate is measured in the field, it is based on a traffic count taken upstream of the queue associated with the system element. This distinction is important for counts made during congested periods because the count of vehicles departing the system element will produce a demand flow rate that is lower than the true rate.

Demand multiplier – The ratio of the daily (weekday–month combination) facility demand to the average daily traffic (or to any combination of day of week and month of year).

Demand starvation – A condition occurring when a signalized approach has adequate capacity but a significant portion of the traffic demand is held upstream and cannot use the capacity provided because of the signalization pattern.

Demand-to-capacity ratio – The ratio of demand volume to capacity for a system element.

Demand volume – The number of vehicles that arrive to use the facility. Under noncongested conditions, demand volume is equal to the observed volume.

Density – The number of vehicles occupying a given length of a lane or roadway at a particular instant. See also *pedestrian density.*

Departure headway – The average time between departures of successive vehicles on a given approach at an all-way STOP-controlled intersection.

Descriptive model – A model that shows how events unfold given a logic that describes how the objects involved will behave.

Design analysis – An application of the HCM to establish the detailed physical features that will allow a new or modified facility to operate at a desired LOS. Inputs are based substantially on proposed design attributes; however, the intermediate- to long-term focus of the analysis will require use of some default values.

Design hour – An hour with a traffic volume that represents a reasonable value for designing the geometric and control elements of a facility.

Design speed – A speed used to design the horizontal and vertical alignments of a highway.

Detection mode – One of two modes—presence or pulse—that determine the duration of the actuation submitted to the controller by the detection unit.

Detection zone – The portion of a signalized intersection approach where a vehicle can be detected by the signal controller (with use of in-pavement loops or other technology), resulting in the display of the green indication for the approach being extended.

Detector – A device used to count or determine the presence of a motorized vehicle, bicycle, or pedestrian.

Deterministic model – A mathematical model that is not subject to randomness. For a given set of inputs, the result from the model is the same with each application.

***D*-factor** – The proportion of traffic moving in the peak direction of travel on a given roadway during the peak hour.

Diamond interchange – An interchange form where one diagonal connection is made for each freeway entry and exit, with one connection per quadrant.

Directional design hour volume – The traffic volume for the design hour in the peak direction of flow.

Directional distribution – A characteristic of traffic that volume may be greater in one direction than in the other during any particular hour on a highway. See also *D-factor*.

Directional flow rate – The flow rate of a highway in one direction.

Directional segment – A length of two-lane highway in one travel direction with homogeneous cross sections and relatively constant demand volume and vehicle mix.

Directional split – See *D-factor*.

Displaced left-turn (DLT) intersection – An alternative intersection that reroutes left turns to crossovers upstream of the central junction; the left-turn traffic streams then approach the central junction to the left of the opposing through movement. DLTs can move left-turn and through vehicles during the same signal phase without conflict.

Distributed intersection – A group of two or more intersections that, by virtue of close spacing and displaced or distributed traffic movements, are operationally interdependent and are thus best analyzed as a single unit.

Diverge – A movement in which a single stream of traffic separates into two streams without the aid of traffic control devices.

Diverge segment – See *freeway diverge segment*.

Diverging diamond interchange (DDI) – A diamond interchange form where through traffic on the arterial switches sides of the street at each of the ramp terminals, allowing left turns to ramps to be made without conflict from opposing through vehicular traffic.

Divided highway – A highway where opposing directions of travel are separated by a physical barrier.

Divided median type – An urban street where opposing directions of travel are separated by a nonrestrictive median (e.g., two-way left-turn lane) or a restrictive median (e.g., raised curb).

Double-crossover diamond interchange – See *diverging diamond interchange*.

Downstream – The direction of traffic flow.

Driver population – The familiarity of motorists with a roadway's geometrics and traffic conditions; for example, commuters or weekend recreational travelers.

Dual entry – A mode of operation (in a multiring controller) in which one phase in each ring must be in service. If a call does not exist in a ring when it crosses the barrier, a phase is selected in that ring to be activated by the controller in a predetermined manner.

Duration – The length of time that a condition persists.

Dwell time – The sum of passenger service time and boarding lost time.

Dwell time variability – The distribution of dwell times at a stop because of fluctuations in passenger demand for buses and routes.

Dynamic speed limits – An ATDM strategy that adjusts speed limits on the basis of real-time traffic, roadway, or weather conditions.

Dynamic traffic assignment model – A descriptive model that is based on an objective (e.g., minimize the travel time or disutility associated with a trip) that is gradually improved over a sequence of iterations until the network reaches a state of equilibrium.

E

Effective available time-space – The available crosswalk time-space, adjusted to account for the effect turning vehicles have on pedestrians.

Effective green time – The time that can be used by vehicles to proceed effectively at the saturation flow rate.

Effective red time – The cycle length minus the effective green time.

Effective walk time – The time that a WALK indication is displayed to a crosswalk, plus the portion of the DON'T WALK indication used by pedestrians to initiate their crossing.

Effective walkway width – The portion of a pedestrian facility's width that is usable for pedestrian circulation.

85th percentile speed – A speed value that is exceeded by 15% of the vehicles in a traffic stream.

Empirical model – A model that describes system performance and that is based on the statistical analysis of field data.

Entrance ramp – See *on-ramp*.

Entry flow – The traffic flow entering a roundabout on the subject approach.

Environmental conditions – Conditions such as adverse weather, bright sunlight directly in drivers' eyes, and abrupt transitions from light to dark (such as at a tunnel entrance on a sunny day) that may cause drivers to slow down and increase their spacing, resulting in a drop in a roadway's capacity.

Event – A bicycle meeting or passing a pedestrian on a shared-use path.

Excess wait time – The average number of minutes transit passengers must wait at a stop past the scheduled departure time.

Exclusive bus lane – A highway or street lane reserved primarily for buses during specified periods. It may be used by other traffic for certain purposes, such as making a right or left turn, or by taxis, motorcycles, or carpools that meet the requirements of the jurisdiction's traffic laws.

Exclusive off-street bicycle paths – Paths physically separated from highway traffic provided for the exclusive use of bicycles.

Exclusive turn lane – A designated left- or right-turn lane used only by vehicles making those turns.

Exit flow – The traffic flow exiting a roundabout to the subject leg.

Exit ramp – See *off-ramp*.

Expected demand – The flow that would arrive at each segment if all queues were stacked vertically (i.e., as if the queues had no upstream impacts).

Experienced travel time – For a given origin–destination movement, the sum of extra distance travel time and the control delay experienced at each junction encountered when an interchange or alternative intersection is traversed.

Extension of effective green – The initial portion of the yellow change interval during which a combination of traffic movements is considered to proceed effectively at the saturation flow rate.

Extent of congestion – The physical length of the congested system.

External section – A freeway section occurring between interchanges (i.e., between the final on-ramp at one interchange and the first off-ramp at the next downstream interchange).

Extra distance travel time – The free-flow travel time required to traverse an interchange or alternative intersection minus the hypothetical shortest-path free-flow travel time making right-angle turns.

F

Facility – A length of roadway, bicycle path, or pedestrian walkway composed of a connected series of points and segments.

Failure rate – The probability that a bus will arrive at a bus stop and find all available loading areas already occupied by other buses.

Far-side stop – A transit stop where transit vehicles cross an intersection before stopping to serve passengers.

Fixed force-off – A mode of split management used with coordinated operations under which force-off points cannot move. Under this mode, uncoordinated phases can utilize unused time from previous phases.

Fixed-object effective width – The sum of the physical width of a fixed object along a walkway or sidewalk, any functionally unusable space associated with the object, and the buffer given it by pedestrians.

Flared approach – At two-way STOP-controlled intersections, a shared right-turn lane that allows right-turning vehicles to complete their movement while other vehicles are occupying the lane.

Floating force-off – A force-off mode under which force-off points can move depending on the demand of previous phases. Under this mode, uncoordinated phases are limited to their defined split times, and all unused time is dedicated to the coordinated phases.

Flow profile – A macroscopic representation of steady traffic flow conditions for the average signal cycle during the specified analysis period.

Flow rate – The equivalent hourly rate at which vehicles or other roadway users pass over a given point or section of a lane or roadway during a given time interval of less than 1 h, usually 15 min.

Flow ratio – The ratio of the actual flow rate to the saturation flow rate for a lane group at an intersection.

Follower density – The number of followers per mile per lane; the following state is defined as a condition in which a vehicle is following its leader by no more than 3 s.

Follow-up headway – The time between the departure of one vehicle from the minor street and the departure of the next vehicle using the same major-street headway, under a condition of continuous queuing on the minor street.

Force-off – A point within a cycle where an actuated phase must end regardless of continued demand. These points in a coordinated cycle ensure that the coordinated phases are provided a minimum amount of green time. See also *fixed force-off* and *floating force-off*.

Four-phase pattern – A type of operation at an all-way STOP-controlled intersection with multilane approaches, where drivers from a given approach enter the intersection together, as right-of-way passes from one approach to the next and each is served in turn.

Free flow – A flow of traffic unaffected by upstream or downstream conditions.

Free-flow speed – **1.** The average speed of vehicles on a given segment, measured under low-volume conditions, when drivers are free to drive at their desired speed and are not constrained by the presence of other vehicles or downstream traffic control devices. **2.** The theoretical speed when both density and flow rate are zero.

Free-flow travel time – **1.** The travel time on a segment that occurs when vehicles travel at the free-flow speed. **2.** The segment's length divided by its free-flow speed.

Freeway – A fully access-controlled, divided highway with a minimum of two lanes (and frequently more) in each direction.

Freeway auxiliary lane – An additional lane on a freeway to connect an on-ramp and an off-ramp.

Freeway diverge segment – A freeway segment in which a single traffic stream divides to form two or more separate traffic streams.

Freeway facility – An extended length of freeway composed of continuously connected basic freeway, weaving, merge, and diverge segments.

Freeway facility capacity – The capacity of the critical segment among those segments composing a defined freeway facility.

Freeway merge segment – A freeway segment in which two or more traffic streams combine to form a single traffic stream.

Freeway section – A portion of a freeway facility extending from one ramp gore point to the next gore point.

Freeway segment capacity – **1.** The maximum 15-min flow rate that produces an acceptable (e.g., 15%) rate of breakdown. **2.** The maximum 15-min flow rate that ensures stable flow for an acceptable percentage (e.g., 85%) of time.

Freeway weaving segment – Freeway segments in which two or more traffic streams traveling in the same general direction cross paths along a significant length of freeway without the aid of traffic control devices (except for guide signs).

Freight – Any commodity being transported.

Frequency – See *transit frequency*.

Frictional effect – See *adjacent friction effect*.

Full DLT intersection – A displaced left-turn intersection where left turns are displaced on both intersecting streets.

Full stop – **1.** At a signalized intersection, the slowing of a vehicle to 0 mi/h (or a crawl speed, if in queue) as a consequence of the change in signal indication from green to red. **2.** At an unsignalized intersection, the slowing of a vehicle to 0 mi/h (or a crawl speed, if in queue) as a consequence of the control device used to regulate the approach. **3.** In a simulation tool, the slowing of a vehicle to less than a specified speed (e.g., 5 mi/h).

Fully actuated control – Signal control in which all phases are actuated and all intersection traffic movements are detected, with the sequence and duration of each phase determined by traffic demand.

Functional class – A grouping of roadways according to the character of service they are intended to provide.

Furniture zone – The portion of the sidewalk between the curb and the area reserved for pedestrian travel; it may be used for landscaping, utilities, or pedestrian amenities.

G

Gap – The space or time between two vehicles, measured from the rear bumper of the front vehicle to the front bumper of the second vehicle. See also *headway*.

Gap acceptance – The process by which a driver accepts an available gap in traffic to perform a maneuver.

Gap out – A type of actuated operation for a given phase under which the phase terminates because of a lack of vehicle calls within the passage time.

General purpose lane – A lane open to all traffic at all times under normal operating conditions.

General terrain – An extended length of highway containing a number of upgrades and downgrades where no single grade is long enough or steep enough to have a significant impact on the operation of the overall segment.

Generalized service volume table – A sketch-planning tool that provides an estimate of the maximum volume a system element can carry at a given level of service, given a default set of assumptions about the system element.

Geometric condition – The spatial characteristics of a facility, including approach grade, the number and width of lanes, lane use, and parking lanes.

Geometric delay – Extra travel time created by geometric features that cause drivers to reduce their speed (e.g., delay experienced where an arterial street makes a sharp turn, causing vehicles to slow, or the delay caused by the indirect route that through vehicles must take through a roundabout).

Gore area – The area located immediately between the left edge of a ramp pavement and the right edge of the roadway pavement at a merge or diverge area.

Grade – The longitudinal slope of a roadway.

Grade separated – Separated vertically from other transportation facilities (e.g., through the use of over- or underpasses).

Green interval – The interval during which a green indication is displayed at a signalized intersection.

Green time – The duration of the green interval.

Green time (*g*/*C*) ratio – The ratio of the effective green time of a phase to the cycle length.

Growth factor – A percentage increase applied to current traffic demands to estimate future demands.

Guidance – The driver's interaction with the vehicle in terms of maintaining a safe path and keeping the vehicle in the proper lane.

H

Half diamond interchange – See *partial diamond interchange.*

HCM dataset – The input data needed to evaluate an urban street facility for one analysis period.

Headway – The time between two successive vehicles as they pass a point on the roadway, measured from the same common feature of both vehicles (for example, the front axle or the front bumper).

Heavy vehicle – A vehicle with more than four wheels touching the pavement during normal operation.

Hidden bottleneck – A segment with a demand-to-capacity ratio greater than 1.0 but an actual flow-to-capacity ratio typically less than 1.0 (or equal to 1.0 in some cases), with no queues forming upstream of the segment.

High-occupancy vehicle (HOV) – A vehicle with a defined minimum number of occupants (>1); HOVs often include buses, taxis, and carpools, when a lane is reserved for their use.

Highway – A general term for denoting a public way for purposes of vehicular travel, including the entire area within the right-of-way.

Hindrance – Discomfort and inconvenience to a bicyclist as a result of meeting, passing, or being overtaken by other pathway users.

Holding area waiting time – The average time that pedestrians wait to cross the street in departing from the subject corner.

Hybrid models – Models used with very large networks that apply microscopic modeling to critical subnetworks and mesoscopic or macroscopic modeling to the connecting facilities.

I

Impedance – The reduction in the potential capacity of lower-rank movements caused by the congestion of a higher-rank movement at a two-way STOP-controlled intersection.

Incident – Any occurrence on a roadway, such as crashes, stalled cars, and debris in the roadway, that impedes the normal flow of traffic.

Incident clearance time – The time from the arrival of the first response vehicle to the time when the incident and service vehicles no longer directly affect travel on the roadway.

Incident delay – Additional travel time experienced as a result of an incident, compared with the no-incident condition.

Incident detection time – The time period starting with the occurrence of an incident and ending when the response officials are notified of the incident.

Incident response time – The time period from the receipt of incident notification by officials to the time the first response vehicle arrives at the scene of the incident.

Incomplete trip – A vehicle that is unable to enter and exit successfully the spatial domain of an analysis within the analysis period.

Incremental delay – The second term of lane group control delay, accounting for delay due to the effect of random, cycle-by-cycle fluctuations in demand that occasionally exceed capacity (i.e., cycle failure) and delay due to sustained oversaturation during the analysis period.

Indication – The signal (e.g., circular green, yellow arrow) shown to a driver at a given point in time to control the driver's movement.

Influence area – **1.** The base length of a freeway weaving segment plus 500 ft upstream of the entry point to the weaving segment and 500 ft downstream of the exit point from the weaving segment; entry and exit points are defined as the points where the appropriate edges of the merging and diverging lanes meet. **2.** From the point where the edges of the travel lanes of merging roadways meet to a point 1,500 ft downstream of that point. **3.** From the point where the edges of the travel lanes of the diverging roadways meet to a point 1,500 ft upstream of that point.

Initial queue – The unmet demand at the beginning of an analysis period, either observed in the field or carried over from the computations of a previous analysis period.

Initial queue delay – The third term of lane group control delay, accounting for delay due to a residual queue identified in a previous analysis period and persisting at the start of the current analysis period. This delay results from the additional time required to clear the initial queue.

Inputs – The data required by a model.

Instantaneous acceleration – An acceleration determined from the relative speeds of a vehicle at time t and time $t - \Delta t$, assuming a constant acceleration during Δt.

Instantaneous speed – A speed determined from the relative positions of a vehicle at time t and time $t - \Delta t$, assuming a constant acceleration during Δt.

Intelligent transportation system (ITS) – Transportation technology that allows drivers and traffic control system operators to gather and use real-time information to improve vehicle navigation, roadway system control, or both.

Intensity of congestion – The amount of congestion experienced by users of a system.

Interchange – A system of interconnecting roadways providing for traffic movement between two or more highways that do not intersect at grade.

Interchange density – The number of interchanges within 3 mi upstream and downstream of the center of the subject weaving segment divided by 6.

Interchange ramp terminal – A junction of a ramp with a surface street serving vehicles entering or exiting a freeway.

Internal link – The segment between two signalized intersections at an interchange ramp terminal.

Internal section – A freeway section occurring within an interchange (for example, between the off-ramp gore and the on-ramp gore in a diamond interchange).

Interrupted-flow facilities – Facilities characterized by traffic signals, STOP signs, YIELD signs, or other fixed causes of periodic delay or interruption to the traffic stream.

Intersection – A point where two or more roadways cross or meet at grade, where vehicular travel between the roadways is accomplished via turning movements, and where right-of-way is typically regulated through the use of traffic control devices.

Intersection delay – The total additional travel time experienced by drivers, passengers, or pedestrians as a result of control measures and interaction with other users of the facility, divided by the volume departing from the corresponding cross section of the facility.

Intersection turn lane – See *exclusive turn lane.*

Interval – A period of time in which all traffic signal indications remain constant.

Island – A defined area between traffic lanes for control of vehicular movements, for toll collection, or for pedestrian refuge.

Isolated intersection – An intersection experiencing negligible influence from upstream signalized intersections, where flow is effectively random over the cycle and without a discernible platoon pattern evident in the cyclic profile of arrivals.

J

Jam density – The maximum density that can be achieved on a segment. It occurs when speed is zero (i.e., when there is no movement of persons or vehicles).

J-turn – See *restricted crossing U-turn intersection.*

Jughandle – An alternative intersection form where direct left turns from the mainline are prohibited and left-turning traffic is rerouted to (*a*) a loop ramp beyond the primary intersection or (*b*) a diamond ramp in advance of the primary intersection that leads to a secondary intersection where left turns are allowed.

Junction – A point where two roadways cross, meet, merge, or diverge at grade.

K

***K*-factor** – The proportion of AADT that occurs during the peak hour.

L

Lagging left-turn phase – A phase sequence in which a left-turn phase is served after the opposing through movement.

Lane 1 – The rightmost mainline lane.

Lane 2 – The lane adjacent to and left of Lane 1.

Lane addition – A location along a roadway where the number of continuous through lanes increases by one or more.

Lane balance – The condition of the number of lanes leaving a diverge point being equal to the number of lanes approaching it, plus one.

Lane distribution – A parameter used when two or more lanes are available for traffic in a single direction and the volume distribution varies between lanes, depending on traffic regulation, traffic composition, speed and volume, the number of and location of access points, the origin–destination patterns of drivers, the development environment, and local driver habits.

Lane drop – A location along a roadway where the number of through lanes is reduced by one or more.

Lane group – A lane or set of lanes designated for separate analysis.

Lane group delay – The control delay for a given lane group.

Lane utilization – The distribution of vehicles among lanes when two or more lanes are available for a movement. See also *prepositioning*.

Lane width – The lateral distance between stripes for a given lane.

Lateral clearance – The lateral distance between the outside edge of a travel lane and a fixed obstruction.

Leading left-turn phase – A phase sequence in which a left-turn phase is served before the opposing through movement.

Leg – A set of lanes at an intersection accommodating all approaching movements to and departing movements from a given direction.

Level of service (LOS) – A quantitative stratification of a performance measure or measures that represent quality of service, measured on an A–F scale, with LOS A representing the best operating conditions from the traveler's perspective and LOS F the worst.

Level-of-service score (LOS score) – A numerical output from a traveler perception model that typically indicates the average rating that travelers would give a transportation facility or service under a given set of conditions.

Level terrain – Any combination of grades and horizontal or vertical alignment that permits heavy vehicles to maintain the same speed as passenger cars, typically containing short grades of no more than 2%.

Light rail mode – A transit mode operated by vehicles that receive power from overhead wires and that run on tracks that can be located at grade within street rights-of-way. See also *streetcar mode*.

Light vehicle – A vehicle with four wheels touching the ground under normal operation, including passenger cars, vans, sport-utility vehicles, and four-wheeled pickup trucks. See also *automobile*.

Limited priority – A condition at a roundabout entry experiencing high levels of both entering and conflicting flow under which circulating traffic adjusts its headways to allow entering vehicles to enter.

Link – A length of roadway between two nodes or points.

Link length – The urban street segment length minus the width of the upstream boundary intersection.

Load factor – The number of passengers occupying a transit vehicle divided by the number of seats on the vehicle.

Loading area – **1.** A curbside space where a single bus can stop to load and unload passengers; bus stops include one or more loading areas. **2.** A curbside space where vehicles can stop briefly to load and unload passengers or freight.

Local street – A street that primarily serves a land-access function.

Local transit service – Transit service making regular stops along a street (typically every 0.25 mi or less).

Loop ramp – A ramp requiring vehicles to execute a left turn by turning right, accomplishing a 90-degree left turn by making a 270-degree right turn.

Lost time – See *clearance lost time, start-up lost time, phase lost time,* and *cycle lost time.*

M

Macroscopic model – A model that considers traffic operations averaged over specified time intervals and specified segments or links without recognizing individual vehicles in the traffic stream.

Mainline – The primary through roadway as distinct from ramps, auxiliary lanes, and collector–distributor roadways.

Mainline output – The maximum number of vehicles that can exit a freeway node, constrained by downstream bottlenecks or by merging traffic.

Major diverge area – A junction where one freeway segment diverges to form two primary freeway segments with multiple lanes.

Major merge area – A junction where two primary freeway segments, each with multiple lanes, merge to form a single freeway segment.

Major street – The street not controlled by STOP signs at a two-way STOP-controlled intersection.

Major weaving segment – A weaving segment where at least three entry and exit legs have two or more lanes.

Managed lanes – A limited number of lanes set aside within a freeway cross section where multiple operational strategies are utilized and actively adjusted as needed to achieve predefined performance objectives. Examples include priced lanes and special-use lanes such as high-occupancy vehicle, express, bus-only, or truck-only lanes.

Max out – A type of actuated operation for a given phase under which the phase terminates because the designated maximum green time for the phase has been reached.

Maximum allowable headway – The maximum time that can elapse between successive calls for service without terminating the phase by gap out.

Maximum green – The maximum length of time that a green signal indication can be displayed in the presence of conflicting demand.

Maximum recall – A form of phase recall under which the controller places a continuous call for vehicle service on the phase. This results in the presentation of the green indication for its maximum duration every cycle.

Maximum weaving length – The length at which weaving turbulence no longer affects the capacity of the weaving segment.

Median – The area in the middle of a roadway separating opposing traffic flows.

Median U-turn (MUT) intersection – An alternative intersection that reroutes all left turns to one-way U-turn crossovers typically located on the major street 500 to 800 ft from the central junction.

Meetings – The number of path users traveling in the opposing direction to the average bicyclist that the average bicyclist passes on the path segment.

Merge – A movement in which two separate streams of traffic combine to form a single stream without the aid of traffic signals or other right-of-way controls.

Merge segment – See *freeway merge segment.*

Mesoscopic model – A mathematical model for the movement of clusters or platoons of vehicles incorporating equations to indicate how the clusters interact.

Michigan left turn – See *median U-turn intersection.*

Microscopic model – A mathematical model that captures the movement of individual vehicles and their car-following, lane choice, and gap acceptance decisions at small time intervals, usually by simulation.

Midblock stop – A transit stop located at a point away from intersections.

Midsegment flow rate – The count of vehicles traveling along the segment during the analysis period, divided by the analysis period duration.

Minimum green – The smallest length of time that a green signal indication will be displayed when a signal phase is activated.

Minimum recall – A form of phase recall under which the controller places a continuous call for vehicle service on the phase and then services the phase until its minimum green interval times out. The phase can be extended if actuations are received.

Minor movement – A vehicle making a specific directional entry into an unsignalized intersection that must yield to other movements.

Minor street – The street controlled by STOP signs at a two-way STOP-controlled intersection.

Misery index – The average of the worst 5% of travel times divided by the free-flow travel time.

Mixed-traffic operation – Operation of a transit mode in lanes shared with other roadway users.

ML access segment – A managed lane segment where vehicles entering and exiting the managed lane must weave with vehicles in the adjacent general purpose lane.

ML basic segment – One of five types of managed lane segment: continuous access, Buffer 1, Buffer 2, Barrier 1, or Barrier 2.

ML diverge segment – A segment on a managed lane facility with nontraversable separation from the general purpose lanes, where traffic exits the managed lane via an off-ramp.

ML merge segment – A segment on a managed lane facility with nontraversable separation from the general purpose lanes, where traffic enters the managed lane via an on-ramp.

ML weave segment – A segment on a managed lane facility with nontraversable separation from the general purpose lanes, where an on-ramp onto the managed lane is followed by an off-ramp from the managed lane and the two are connected by an auxiliary lane.

Mobility – The movement of people and goods.

Mode – See *travel mode*.

Mode group – One of five categories of users of a shared-use pathway: pedestrians, bicyclists, inline skaters, runners, and child bicyclists.

Model – A procedure that uses one or more algorithms to produce a set of numerical outputs describing the operation of a segment or system, given a set of numerical inputs.

Model application – The physical configuration and operational conditions to which a traffic analysis tool is applied.

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

Motorized vehicle mode – A travel mode that includes all motorized vehicles using a roadway. Submodes of the motorized vehicle mode include automobiles, trucks, and public transit vehicles operating on street.

Motorized vehicles – Automobiles, light and heavy trucks, recreational vehicles, buses, and motorcycles.

Mountainous terrain – Any combination of grades and horizontal and vertical alignment that causes heavy vehicles to operate at crawl speed for significant distances or at frequent intervals.

Movement – The direction taken by a vehicle at an intersection (i.e., through, left turn, right turn, U-turn).

Movement capacity – The capacity of a specific traffic stream at a STOP-controlled intersection approach, assuming that the traffic has exclusive use of a separate lane.

Movement group – An organization of traffic movements at a signalized intersection to facilitate data entry. A separate movement group is established for (*a*) each turn movement with one or more exclusive turn lanes and (*b*) the through movement (inclusive of any turn movements that share a lane).

Move-up time – The time it takes a vehicle to move from second position into first position on an approach to an all-way STOP-controlled intersection.

Multilane highway – A highway with at least two lanes for the exclusive use of traffic in each direction, with no control or partial control of access, but that may have periodic interruptions to flow at signalized intersections no closer than 2 mi.

Multilane roundabout – A roundabout with more than one lane on at least one entry and at least part of the circulatory roadway.

Multimodal – Being used by more than one travel mode.

Multimodal analysis – A type of HCM analysis under which the LOS of each travel mode on a facility is evaluated simultaneously.

Multiple weaving segment – A portion of a freeway where a series of closely spaced merge and diverge areas creates overlapping weaving movements (between different merge–diverge pairs).

N

Navigation – Planning and executing a trip.

Near-side stop – A transit stop located on the approach side of an intersection. Transit vehicles stop to serve passengers before crossing the intersection.

Node – The endpoint of a link. See also *point*.

Non–severe weather – Weather conditions that generate no capacity, demand, or speed adjustments (i.e., weather conditions that have not been shown to reduce capacity by at least 4%).

Nonlocal transit service – Transit service on routes with longer stop spacing than local service (e.g., limited-stop, bus rapid transit, or express routes).

Nonrecurring congestion – Congestion that occurs due to infrequent or one-time events (e.g., incidents, work zones, severe weather) that block lanes or otherwise temporarily reduce a facility's capacity.

Nonrestrictive median – A median (e.g., a two-way left-turn lane) that does not prevent or discourage vehicles from crossing the opposing traffic lanes.

Nonweaving flow – The traffic movements in a weaving segment that are not engaged in weaving movements.

Nonweaving movement – A traffic flow within a weaving segment that does not need to cross paths with another traffic flow while traversing the segment.

No-passing zone – A segment of a two-lane, two-way highway along which passing is prohibited in one or both directions.

Normative model – A mathematical model that identifies a set of parameters providing the best system performance.

O

Off-line bus stop – A bus stop where buses stop out of the travel lane.

Off-ramp – A ramp–freeway junction that accommodates diverging maneuvers.

Offset – The time that the reference phase begins (or ends) relative to the system master time zero.

Off-street pedestrian and bicycle facilities – Facilities used only by nonmotorized modes, on which the characteristics of motor vehicle traffic do not play a strong role in determining the quality of service from the perspective of bicyclists and pedestrians.

One-sided weaving segment – A weaving segment in which no weaving maneuvers require more than two lane changes to be completed successfully and in which the on-ramp and off-ramp are located on the same side of the freeway.

One-stage gap acceptance – A condition at a two-way STOP-controlled intersection requiring minor-street through and left-turning drivers to complete their maneuver in one movement and to evaluate gaps in both major-street directions simultaneously.

On-line bus stop – A bus stop where buses stop wholly or partially in the travel lane.

On-ramp – A ramp–freeway junction that accommodates merging maneuvers.

On-street transitway – A portion of a street right-of-way dedicated to the transit mode, physically segregated from other traffic, and located in the median or adjacent to one side of the street.

On-time arrival – **1.** A trip that arrives within a defined travel time. **2.** For scheduled public transit service, a trip that arrives by the scheduled time.

Operational analysis – An application of an HCM methodology under which the user supplies detailed inputs to HCM procedures, with no or minimal use of default values.

Operational mode – The manner in which the controller serves turning movements. See *protected mode, permitted mode,* and *protected–permitted mode.*

Opposing approach – At an all-way STOP-controlled intersection, the approach approximately 180 degrees opposite the subject approach.

Opposing flow rate – The flow rate for the direction of travel opposite to the direction under analysis.

Outputs – The performance measures produced by a model.

Overflow queue – Queued vehicles left over after a green phase at a signalized intersection.

Oversaturated flow – Traffic flow where (*a*) the arrival flow rate exceeds the capacity of a point or segment, (*b*) a queue created from a prior breakdown of a facility has not yet dissipated, or (*c*) traffic flow is affected by downstream conditions.

P

Parclo A interchange – A partial cloverleaf interchange form where the loop ramps on the mainline are located in advance of the crossover.

Parclo AB interchange – A partial cloverleaf interchange form where loop ramps on the mainline are located on the same side of the crossroad, one in advance of the crossroad for its direction of travel and the other beyond.

Parclo B interchange – A partial cloverleaf interchange form where the loop ramps on the mainline are located beyond the crossover.

Partial cloverleaf interchange (parclo) – An interchange with one to three (typically two) loop ramps and two to four diagonal ramps, with major turning movements desirably being made by right-turn exits and entrances.

Partial diamond interchange – A diamond interchange with fewer than four ramps, so that not all of the freeway–street or street–freeway movements are served.

Partial DLT intersection – A displaced left-turn intersection where left turns are displaced on one of the two intersecting streets.

Partial stop – A situation where a vehicle slows as it approaches the back of a queue but does not come to a full stop.

Passage time – The maximum amount of time one vehicle actuation can extend the green interval while green is displayed. It is input for each actuated signal phase; also referred to as vehicle interval, extension interval, extension, or unit extension.

Passenger car – Federal Highway Administration Vehicle Class 2.

Passenger car equivalent – The number of passenger cars that will result in the same operational conditions as a single heavy vehicle of a particular type under identical roadway, traffic, and control conditions.

Passenger load factor – See *load factor*.

Passenger service time – Time for passenger loading, unloading, and fare payment, as well as time spent opening and closing the doors. See also *dwell time*.

Passenger trip length – The average distance traveled by a passenger on board a transit vehicle.

Passing lane – A lane added to improve passing opportunities in one direction of travel on a conventional two-lane highway.

Pavement condition rating – A description of the road surface in terms of ride quality and surface defects.

Peak hour – The hour of the day in which the maximum volume occurs. See also *analysis hour*.

Peak hour factor (PHF) – The hourly volume during the analysis hour divided by the peak 15-min flow rate within the analysis hour; a measure of traffic demand fluctuation within the analysis hour.

Pedestrian – An individual traveling on foot.

Pedestrian circulation route – A space used by pedestrians crossing a pedestrian plaza.

Pedestrian clear interval – Time provided for pedestrians who depart the curb during the WALK indication to reach the opposite curb (or the median). A flashing DON'T WALK indication is displayed during this interval.

Pedestrian crosswalk – A connection between pedestrian facilities across sections of roadway used by automobiles, bicycles, or transit vehicles. Crosswalks can be marked or unmarked.

Pedestrian density – The number of pedestrians per unit of area within a walkway or queuing area.

Pedestrian flow rate – The number of pedestrians passing a point per unit of time. See also *unit width flow rate*.

Pedestrian LOS score – See *level-of-service score*.

Pedestrian mode – A travel mode under which a journey (or part of a journey) is made on foot along a roadway or pedestrian facility.

Pedestrian overpass – A grade-separated pedestrian facility over such barriers as wide or high-speed roadways, railroad tracks, busways, or topographic features.

Pedestrian plaza – A large, paved area that serves multiple functions, including pedestrian circulation, special events, and seating.

Pedestrian queuing area – See *queuing area*.

Pedestrian recall – A form of phase recall where the controller places a continuous call for pedestrian service on the phase and then services the phase for at least a length of time equal to its walk and pedestrian clear intervals (longer if vehicle detections are received).

Pedestrian service time – The elapsed time starting with the first pedestrian's departure from the corner to the last pedestrian's arrival at the far side of the crosswalk.

Pedestrian space – The average area provided for pedestrians in a moving pedestrian stream or pedestrian queue.

Pedestrian start-up time – The time for a platoon of pedestrians to get under way following the beginning of the walk interval.

Pedestrian street – See *pedestrian zone*.

Pedestrian underpass – A grade-separated pedestrian facility under such barriers as wide or high-speed roadways, railroad tracks, busways, or topographic features.

Pedestrian walkway – See *walkways*.

Pedestrian zone – Streets dedicated to pedestrian use on a full- or part-time basis.

Percentile travel time index – The travel time index that the specified percentage of observations in the travel time distribution fall at or below. For example, an 85th percentile travel time index is exceeded only 15% of the time in the travel time distribution.

Percent of free-flow speed – The average travel speed divided by the free-flow speed.

Percent time-spent-following – The average percentage of total travel time that vehicles must travel in platoons behind slower vehicles because of inability to pass on a two-lane highway.

Performance measure – A quantitative or qualitative characterization of some aspect of the service provided to a specific road user group.

Permanent traffic recorder – A location where traffic volume data (and potentially speed, vehicle classification, and other data) are collected 24 hours a day, 7 days a week and subsequently archived.

Permitted mode – An operational mode requiring turning drivers to yield to conflicting vehicles, bicycles, and pedestrians before completing the turn.

Permitted plus protected – See *protected–permitted mode.*

Person capacity – The maximum number of persons who can pass a given point during a specified period under prevailing conditions.

Phase – The green, yellow change, and red clearance intervals in a cycle that are assigned to a specified traffic movement (or movements).

Phase flow ratio – The largest flow ratio of all lane groups served during the phase.

Phase lost time – The sum of the clearance lost time and start-up lost time.

Phase pair – See *barrier pair.*

Phase pattern – The alternation of right-of-way among various traffic streams at an all-way STOP-controlled intersection.

Phase recall – A setting that causes the controller to place a call for a specified phase each time the controller is servicing a conflicting phase. See also *maximum recall, minimum recall,* and *pedestrian recall.*

Phase sequence – The order of phases in a ring.

Planning analysis – An application of the HCM generally directed toward broad issues such as initial problem identification (e.g., screening a large number of locations for potential operations deficiencies), long-range analyses, and regional and statewide performance monitoring. Nearly all inputs to the analysis may be defaulted.

Planning time index – The 95th percentile travel time index.

Platoon – A group of vehicles or pedestrians traveling together as a group, either voluntarily or involuntarily because of signal control, geometrics, or other factors.

Platoon decay – The degradation of a platoon traveling along an urban street due to the effects of vehicles turning into and out of access points.

Platoon dispersion – The degradation of a platoon with increasing distance traveled along an urban street, due to differing speeds of vehicles within the platoon.

Platoon ratio – A description of the quality of signal progression computed as the demand flow rate during the green indication divided by the average demand flow rate.

Point – A place along a facility where (*a*) conflicting traffic streams cross, merge, or diverge; (*b*) a single traffic stream is regulated by a traffic control device; or (*c*) there is a significant change in the segment capacity (e.g., lane drop, lane addition, narrow bridge, significant upgrade, start or end of a ramp influence area).

Postbreakdown flow rate – See *queue discharge flow rate.*

Potential capacity – The capacity of a specific movement at a STOP-controlled intersection approach, assuming that it is unimpeded by pedestrian or higher-rank movements and has exclusive use of a separate lane.

Prebreakdown capacity – The 15-min flow rate immediately preceding a breakdown event.

Precision – The size of the estimation range for a measured quantity.

Preemption – The interruption of normal traffic signal operations (breaking coordination) to serve a preferred vehicle, without regard for the state of the signal.

Preliminary engineering analysis – An HCM application conducted to support planning decisions related to roadway design concept and scope, when alternatives analyses are performed, or to assess proposed systemic policies. Many of the inputs to the analysis will be defaulted.

Prepositioning – A deliberate driver choice of one lane over another at an intersection in anticipation of a turn at a downstream intersection.

Presence detection – A detection mode under which the actuation starts with the vehicle arriving in the detection zone and ends with the vehicle leaving the detection zone.

Pretimed control – A fixed sequence of phases that are displayed in repetitive order.

Prevailing condition – The geometric, traffic, control, and environmental conditions during the analysis period.

Priority reversal – A condition at a roundabout entry experiencing high levels of both entering and conflicting flow, where entering traffic forces circulating traffic to yield.

Probability density function – A function giving the number or percent of all observations in the travel time distribution within a specified travel time (or travel time index) bin.

Probe vehicles – Vehicles within a traffic stream whose position is known continuously or at specific detector locations that can be used to determine travel times and speeds between defined locations.

Progression – The act of various controllers providing specific green indications in accordance with a time schedule to permit continuous operation of groups of vehicles along the street at a planned speed.

Protected mode – An operational mode under which turning drivers are given the right-of-way during the associated turn phase while all conflicting movements are required to stop.

Protected–permitted mode – An operational mode combining the permitted and protected modes. Turning drivers have the right-of-way during the associated turn phase. Turning drivers can also complete the turn "permissively" when the adjacent through movement receives its circular green (or when the turning driver receives a flashing yellow arrow) indication.

Pseudo right turns – A concept applied to the analysis of full DLT intersections with the HCM signalized intersection model, where the displaced left turns are modeled as right turns from the opposing approach.

Pulse detection – A detection mode under which the actuation starts and ends with the vehicle arriving at the detector (the actuation consists of a short "on" pulse of 0.10 to 0.15 s).

Q

Quality of service – A description of how well a transportation facility or service operates from a traveler's perspective.

Quantity of service – The utilization of the transportation system in terms of the number of people using the system, the distance they travel, and the time they require to travel.

Queue – A line of vehicles, bicycles, or persons waiting to be served because of traffic control, a bottleneck, or other reasons.

Queue accumulation polygon – A graphic tool for describing the deterministic relationship between vehicle arrivals, departures, queue service time, and delay.

Queue delay – **1.** The length of time that a vehicle spends in a queued state. **2.** When queue delay is computed from vehicle trajectories, it is the accumulated time step delay over all time steps in which the vehicle is in a queue.

Queue discharge capacity drop – The percent reduction in the prebreakdown capacity following breakdown at an active bottleneck.

Queue discharge flow – Traffic flow that has just passed through a bottleneck and, in the absence of another bottleneck downstream, is accelerating back to the facility's free-flow speed.

Queue discharge flow rate – The average 15-min flow rate during oversaturated conditions (i.e., during the time interval after breakdown and before recovery).

Queued state – A condition when a vehicle is within one car length of a stopped vehicle or the stop bar and is itself about to stop.

Queue jump – A short bus lane section (often shared with a right-turn lane), in combination with an advance green indication for the lane, that allows buses to move past a queue of cars at a signal.

Queue length – The distance between the upstream and downstream ends of the queue.

Queue spillback – A condition where the back of a queue extends beyond the available storage length, resulting in potential interference with upstream traffic movements. See also *cyclic spillback*, *sustained spillback*, and *turn bay spillback*.

Queue storage ratio – The maximum back of queue as a proportion of the available storage on the subject lane or link.

Queuing area – A place where pedestrians stand while waiting to be served, such as at the corner of a signalized intersection.

R

Ramp – **1.** A dedicated roadway providing a connection between two other roadways; at least one of the roadways a ramp connects is typically a high-speed facility such as a freeway, multilane highway, or C-D roadway.

2. A sloped walkway connecting pedestrian facilities at different elevations.

Ramp–freeway junction – The point of connection between a ramp and a high-speed facility, such as a freeway, multilane highway, or C-D roadway, designed for high-speed merging or diverging without control.

Ramp meter – A traffic signal that controls the entry of vehicles from a ramp onto a limited-access facility; the signal allows one or two vehicles to enter on each green or green flash.

Ramp roadway – See *ramp*.

Ramp–street junction – See *interchange ramp terminal*.

Ramp weave – A weaving segment where a one-lane on-ramp is closely followed by a one-lane off-ramp, connected by a continuous freeway auxiliary lane. All weaving drivers must execute a lane change across the lane line separating the freeway auxiliary lane from the right lane of the freeway mainline.

Rank – The hierarchy of right-of-way among conflicting traffic streams at a two-way STOP-controlled intersection.

Reasonable expectancy – The concept that the stated capacity for a given system element is one that can be achieved repeatedly during peak periods rather than being the absolute maximum flow rate that could be observed.

Receiving lanes – Lanes departing an intersection.

Recovery – **1.** A return of freeway operations to near prebreakdown conditions for at least 15 min. **2.** A return of the prevailing speed to within 10% of the free-flow speed for a sustained period of at least 15 min, without the presence of queuing upstream of the bottleneck.

Recreational vehicle – A heavy vehicle, generally operated by a private motorist, for transporting recreational equipment or facilities; examples include campers, motor homes, and vehicles towing boat trailers.

Recurring congestion – Congestion that regularly occurs at a particular location and time of day due, for example, to a bottleneck.

Red clearance interval – This interval follows the yellow change interval and is optionally used to provide additional time before conflicting movements receive a green indication.

Red time – The period in the signal cycle during which, for a given phase or lane group, the signal is red.

Reduced conflict intersection – See *restricted crossing U-turn intersection*.

Reentry delay – Delay experienced by buses leaving a bus stop, when they must wait for a gap in traffic before reentering the travel lane.

Reference phase – One of the two coordinated phases (i.e., Phase 2 or 6).

Regression model – A model that uses field or simulated data to derive statistical relationships between particular model inputs and performance measures such as capacity and delay.

Reliability rating – The percentage of vehicle miles traveled on the facility that experiences a travel time index less than 1.33 (freeways) or 2.50 (urban streets).

Reliability reporting period – The specific set of days over which travel time reliability is computed (e.g., all nonholiday weekdays in a year).

Residual queue – The unmet demand at the end of an analysis period resulting from operation while demand exceeded capacity.

Rest-in-walk mode – A controller mode in which the phase will dwell in walk as long as there are no conflicting calls. When a conflicting call is received, the pedestrian clear interval will time to its setting value before ending the phase.

Restricted crossing U-turn (RCUT) intersection – An alternative intersection that reroutes the minor-street left turn and through movements to one-way U-turn crossovers on the major street. These crossovers are typically located 450 ft or more from the central junction.

Restrictive median – A median (e.g., a raised curb) that prevents or discourages vehicles from crossing the opposing traffic lanes.

Reverse priority – See *priority reversal*.

Right-of-way – **1.** The permitting of vehicles or pedestrians to proceed in a lawful manner in preference to other vehicles or pedestrians by the display of a sign or signal indications. **2.** Land used for the provision of a public roadway.

Right-turn bypass lane – At a roundabout, a lane provided adjacent to but separated from the circulatory roadway. It allows right-turning movements to bypass the roundabout.

Right turn on red – The ability to make a right turn at a signalized intersection when a red indication is displayed, after stopping and only when no conflicting motorized vehicle, bicycle, or pedestrian traffic is present.

Ring – A set of phases operating in sequence.

Roadside obstruction – An object or barrier along a roadside or median that affects traffic flow, whether continuous (e.g., a retaining wall) or not continuous (e.g., light supports or bridge abutments).

Roadway – That portion of a highway improved, designed, or ordinarily used for vehicular travel and parking lanes but exclusive of the sidewalk, berm, or shoulder even though such sidewalk, berm, or shoulder is used by persons riding bicycles or other human-powered vehicles.

Roadway characteristic – A geometric characteristic of a street or highway, including the type of facility, number and width of lanes (by direction), shoulder widths and lateral clearances, design speed, and horizontal and vertical alignments.

Roadway metering – The storing of surges in demand at various points in the transportation network. Typical examples of roadway metering include freeway on-ramp metering, freeway-to-freeway ramp metering, freeway mainline metering, peak period freeway ramp closures, and arterial signal metering.

Roadway occupancy – **1.** The proportion of roadway length covered by vehicles. **2.** The proportion of time a roadway cross section is occupied by vehicles.

Rolling terrain – Any combination of grades and horizontal or vertical alignment that causes heavy vehicles to reduce their speed substantially below that of passenger cars but that does not cause heavy vehicles to operate at crawl speeds for any significant length of time or at frequent intervals.

Roundabout – An intersection with a generally circular shape, characterized by yield on entry and circulation around a central island.

Rubbernecking – The slowing of motorists to observe a traffic incident.

Running speed – See *average running speed.*

Running time – The time a vehicle spends in motion.

Rural – **1.** An area with widely scattered development and a low density of housing and employment. **2.** A location outside any urbanized area boundary, as defined by the Federal Highway Administration.

S

Saturation flow rate – The equivalent hourly rate at which previously queued vehicles can traverse an intersection approach under prevailing conditions, assuming that the green indication is available at all times and no lost times are experienced.

Saturation flow rate, adjusted – The saturation flow rate under prevailing geometric and traffic conditions.

Saturation flow rate, base – The expected average flow rate for a through-traffic lane for exceptionally favorable geometric and traffic conditions (no grade, no trucks, and so forth).

Saturation headway – **1.** At a signalized intersection, the average headway between vehicles occurring after the fourth vehicle in the queue and continuing until the last vehicle in the initial queue clears the intersection. **2.** At an all-way STOP-controlled intersection, the time between departures of successive vehicles on a given approach for a particular case, assuming a continuous queue.

Scenario – **1.** A single instance of a study period for the facility, with a unique combination of traffic demands, capacities, geometries, and free-flow speeds represented in its analysis periods. **2.** See *model application.*

Scenario, base – A set of parameters representing the facility's calibrated operating conditions during one study period. All other scenarios are developed by adjusting the base scenario's inputs to reflect the effects of varying demand, weather, incidents, work zones, or a combination occurring in other study periods. See also *seed file* and *base dataset.*

Scenario generation – The enumeration of the different operational conditions on a freeway or urban street facility on the basis of varying combinations of factors affecting the facility travel time.

Section – A portion of a freeway facility between points where either demand or capacity changes.

Section, study – The length of facility over which reliability is to be computed.

Seed file – The inputs provided to a computational engine corresponding to the base scenario.

Segment – **1.** For interrupted-flow facilities, a link and its boundary points. **2.** For uninterrupted-flow facilities, a portion of a facility between two points.

Segment delay – **1.** The delay experienced by a vehicle since it left the upstream node (usually another signal), including traffic delay, incident delay, control delay, and geometric delay. **2.** When calculated from vehicle trajectories, the time actually 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 time 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.

Segment initialization – The process of determining the appropriate number of vehicles in each segment as a precursor to estimating the number of vehicles on each freeway segment for each time step under oversaturated conditions.

Semiactuated control – Signal control in which some approaches (typically on the minor street) have detectors and some approaches (typically on the major street) have no detectors.

Semi–standard deviation – A one-sided standard deviation, with the reference point being free-flow travel time instead of the mean.

Sensitivity analysis – A technique for exploring how model outputs change in response to changes in model inputs, implemented by varying one input at a time over its reasonable range while holding all other inputs constant.

Service flow rate – The maximum directional rate of flow that can be sustained in a given segment under prevailing roadway, traffic, and control conditions without violating the criteria for a given LOS.

Service measure – A performance measure used to define LOS for a transportation system element.

Service time – At an all-way STOP-controlled intersection, the average time spent by a vehicle in first position waiting to depart, equal to the departure headway minus the move-up time.

Service volume – The maximum number of vehicles that a system element can serve at a given LOS, given a set of assumed conditions.

Service volume table – See *generalized service volume table.*

Severe weather – Weather conditions that generate capacity, demand, or speed adjustments (i.e., weather conditions that have been shown to reduce capacity by at least 4%).

Shared lane – **1.** A lane shared by more than one movement. **2.** A bicycle facility where bicycles share a travel lane with motorized vehicle traffic.

Shared-lane capacity – The capacity of a lane at an intersection that is shared by two or three movements.

Shared-use path – A path physically separated from highway traffic for the use of pedestrians, bicyclists, runners, inline skaters, and other nonmotorized users.

Shelter – A structure with a roof and (typically) three enclosed sides that protects waiting transit passengers from wind, rain, and sun.

Shock wave – A change or discontinuity in traffic conditions. For example, a shock wave is generated when the signal turns red, and it moves upstream as vehicles arriving at the queue slow down. A shock wave is also generated when the signal turns green, and it moves downstream as the first set of vehicles discharge from the signal.

Short length – The distance within a weaving segment over which lane changing is not prohibited or dissuaded by markings.

Shoulder – A portion of the roadway contiguous with the traveled way for accommodation of stopped vehicles; emergency use; and lateral support of the subbase, base, and surface courses.

Shoulder bypass lane – A portion of the paved shoulder opposite the minor-road leg at a three-leg intersection, marked as a lane for through traffic to bypass vehicles that are slowing or stopped to make a left turn.

Shy distance – The buffer that pedestrians give themselves to avoid accidentally stepping off the curb, brushing against a building face, or getting too close to pedestrians standing under awnings or window shopping.

Sidepath – A shared pedestrian–bicycle path located parallel and in proximity to a roadway.

Side street – See *minor street.*

Sidewalk – A pedestrian facility located parallel and in proximity to a roadway.

Signal priority – See *traffic signal priority.*

Simulation – See *traffic simulation.*

Simultaneous gap out – A controller mode requiring that both phases reach a point of being committed to terminate (via gap out, max out, or force-off) at the same time.

Single entry – A mode of operation (in a multiring controller) in which a phase in one ring can be selected and timed alone if there is no demand for service in a nonconflicting phase on the parallel ring(s).

Single-lane roundabout – A roundabout that has single lanes on all entries and one circulatory lane.

Single-point urban interchange (SPUI) – A diamond interchange that combines all the left-turning ramp movements into a single signalized intersection.

Single-stage gap acceptance – See *one-stage gap acceptance.*

Single-unit trucks – **1.** Trucks on a single frame. **2.** Federal Highway Administration Vehicle Classifications 5–7.

Sketch-planning tools – Tools that produce general order-of-magnitude estimates of travel demand and transportation system performance under different transportation system improvement alternatives.

Space – See *pedestrian space.*

Space gap – See *gap.*

Space mean speed – An average speed based on the average travel time of vehicles to traverse a length of roadway.

Spacing – The distance between two successive vehicles in a traffic lane, measured from the same common feature of the vehicles (e.g., rear axle, front axle, or front bumper).

Spatial stop rate – The ratio of stop count to facility length. See also *stop rate.*

Spatial variability – Variability in measured values, such as the percentage of trucks in the traffic stream, from one location to another within an area or from one area to another.

Special events – Sources of high demand that occur at known times relatively infrequently, resulting in traffic flow patterns that vary substantially from the typical situation.

Specific grade – A roadway segment with a grade that is steep or long enough to require separate analysis.

Speed – A rate of motion expressed as distance per unit of time.

Speed adjustment factor – An adjustment to base free-flow speed to reflect the effects of severe weather, incidents, and work zones. It can also be used to calibrate the freeway facility model to reflect local conditions.

Speed harmonization – The dynamic slowing of traffic in advance of queues, incidents, and lane closures and the direction of traffic to the remaining lanes.

Spillback – See *queue spillback.*

Spillover – A condition occurring when pedestrians begin to use more than the provided sidewalk or walkway space (e.g., by stepping into the street) to travel at their desired speed.

Split – The segment of the cycle length allocated to each phase or interval that may occur. In an actuated controller unit, split is the time in the cycle allocated to a phase—the sum of the green, yellow change, and red clearance intervals for a phase.

Split-diamond interchange – A diamond interchange in which freeway entry and exit ramps are separated at the street level, creating four intersections.

Split phasing – A phase sequence in which one phase serves all movements on one approach and a second phase serves all movements on the opposing approach.

Splitter island – A raised or painted area on a roundabout approach used to separate entering from exiting traffic, deflect and slow entering traffic, and provide storage space for pedestrians crossing that intersection approach in two stages.

Stairway – A pedestrian facility that ascends a grade via a series of steps and landings.

Start-up lost time – The additional time consumed by the first few vehicles in a queue whose headway exceeds the saturation headway because of the need to react to the initiation of the green interval and accelerate.

Static flow model – A mathematical model in which the traffic flow rate and origin–destination volumes are constant.

Stochastic – Involving an element of randomness.

Stochastic model – A mathematical model that uses random number generation for the determination of at least one parameter.

Stop-line detector length – The length of the detection zone used to extend the green indication.

Stopped delay – The amount of time that a vehicle is stopped. When calculated from vehicle trajectories, it is equal to the time step delay on any step in which the vehicle is in a stopped state. Time step delays accumulated over all time steps in which the vehicle was in the stopped state represent the stopped delay for that vehicle.

Stopped state – A condition when a vehicle is traveling at less than 5 mi/h.

Stop rate – The count of full stops divided by the number of vehicles served. See also *spatial stop rate.*

Storage length – The length of turn lane available for storing queued vehicles.

Street – See *highway.*

Streetcar mode – A transit mode operated by vehicles that receive power from overhead wires and run on tracks. Compared with light rail, streetcars are generally shorter and narrower, are more likely to have onboard fare collection, make more frequent stops, and are more likely to operate in mixed traffic.

Street corner – The area encompassed within the intersection of two sidewalks.

Study period – The time interval within a day for which facility performance is evaluated, consisting of one or more consecutive analysis periods.

Subject approach – The approach under study at two-way and all-way STOP-controlled intersections.

Suburban street – A street with low-density driveway access on the periphery of an urban area.

Superstreet – See *restricted crossing U-turn intersection.*

Sustained spillback – A result of oversaturation, where a queue does not dissipate at the end of each cycle but remains present until the downstream capacity is increased or the upstream demand is reduced.

Synchronized street – See *restricted crossing U-turn intersection.*

System – All the transportation facilities and modes within a particular region.

System elements – Components of a transportation system, including points, segments, facilities, corridors, and areas.

T

Target speed – In a simulation tool, the speed at which a driver would prefer to travel; it differs from the free-flow speed in that most simulation tools apply a "driver aggressiveness" factor to the free-flow speed to determine a target speed.

Temporal variability – Variability in measured values, such as hourly traffic volumes, that occurs from day to day or month to month at a given location.

Terrain – See *general terrain, level terrain, rolling terrain,* and *mountainous terrain.*

Three-level diamond interchange – A diamond interchange with two divided levels so that both facilities provide continuous through movements.

Threshold delay – The excess travel time that occurs beyond a defined speed or LOS established by norm.

Throughput – The number of persons or vehicles passing a point on a transportation facility during a given time period.

Through vehicles – All vehicles passing directly through a street segment and not turning.

Thru turn – See *median U-turn intersection.*

Tight urban diamond interchange – A diamond interchange with a separation of less than 400 ft between the two intersections.

Time gap – See *gap.*

Time interval – See *analysis period.*

Time interval scale factor – The ratio of the total facility entrance counts to total facility exit counts.

Time mean speed – The average speed of vehicles observed passing a point on a highway.

Time step delay – The length of a time step minus the time it would have taken a vehicle to cover the distance traveled in the step at the target speed.

Time-space – In pedestrian analysis, the product of time and space, combining the constraints of physical design (which limits available space) and signal operation (which limits available time).

Time–space domain – A specification of the freeway sections and segments included in the defined facility and an identification of the time intervals for which the analysis is to be conducted.

Time-varying flow model – A simulation model in which flow changes with time.

Toll plaza – An area along, at the entrance to, or at the exit from a tolled facility where tolls are collected, particularly areas consisting of a row of tollbooths across the roadway.

Tool – See *traffic analysis tool.*

Total lateral clearance (TLC) – The sum of the right-side and left-side lateral clearances along a multilane highway.

Total lost time – See *lost time.*

Total ramp density – The average number of on-ramp, off-ramp, major merge, and major diverge junctions per mile.

Tractor trailers – **1.** Trucks consisting of two or more units, one of which is a tractor or straight truck power unit and the others being trailers. **2.** Federal Highway Administration Vehicle Classifications 8–13.

Traffic analysis tool – A software product used for traffic analysis that includes, at a minimum, a computational engine and a user interface.

Traffic circle – A circular intersection lacking one or more characteristics of a roundabout.

Traffic composition – The mix of cars, buses, trucks, carpools, bicycles, and pedestrians in the network.

Traffic condition – A characteristic of traffic flow, including distribution of vehicle types in the traffic stream, directional distribution of traffic, lane use distribution of traffic, and type of driver population on a given facility.

Traffic control device – A sign, signal, marking, or other device used to regulate, warn, or guide traffic.

Traffic delay – Extra travel time resulting from the interaction of vehicles, which causes drivers to reduce their speed below the free-flow speed.

Traffic incident – See *incident.*

Traffic pressure – The display of aggressive driving behavior for a large number of drivers during high-demand traffic conditions. Under such conditions, a large number of drivers accept shorter headways during queue discharge than they would under different circumstances.

Traffic signal delay – Delay experienced by a bus that arrives at a near-side stop during the green interval, serves its passengers during portions of the green and red intervals, and then must wait for the traffic signal to turn green again before proceeding. See also *control delay.*

Traffic signal optimization tool – A tool primarily designed to develop optimal signal phasing and timing plans for isolated signalized intersections, arterial streets, or signal networks.

Traffic signal priority – Signal timing adjustments to accommodate preferred vehicles while maintaining coordination.

Traffic simulation – A mathematical representation of a road transportation system, implemented as computer software. Depending on the degree to which the movements of individual vehicles are aggregated, traffic simulation tools can be characterized as *microscopic, mesoscopic,* or *macroscopic.*

Transit frequency – The count of scheduled fixed-route transit vehicles that stop on or near an urban street segment during the analysis period.

Transition – The process of entering into a coordinated signal timing plan from free operations, changing between two plans, or returning to a plan after the loss of coordination.

Transit LOS score – See *level-of-service score.*

Transit mode – A submode of the motorized vehicle mode in which transit vehicles (including buses, streetcars, and street-running light rail) stop at regular intervals along the roadway to pick up and drop off passengers.

Transit reliability – A measure of the time performance and the regularity of headways between successive transit vehicles affecting the length of time passengers must wait at a transit stop as well as the consistency of a passenger's arrival time at a destination.

Transit route – A designated path to which a transit vehicle is assigned. Several routes may traverse a single portion of roadway.

Transit signal priority – See *traffic signal priority.*

Transitway – See *on-street transitway.*

Travel demand models – Models that forecast long-term travel demand on the basis of current conditions and projections of socioeconomic characteristics and changes in transportation system design.

Traveler information systems – An integration of technologies that allow the general public to access real-time or near real-time data on traffic factors such as incident conditions, travel time, and speed.

Traveler perception model – A model that estimates the average response or range of responses of travelers to a given set of conditions (typically operational or design in nature). See also *level-of-service score.*

Travel mode – **1.** A transport category characterized by specific right-of-way, technological, and operational features. **2.** A particular form of travel, for example, walking, bicycling, traveling by automobile, or traveling by bus.

Travel speed – See *average travel speed.*

Travel time – **1.** The average time spent by vehicles traversing a highway segment, including control delay. **2.** The time required for a vehicle to travel the full length of the freeway facility from mainline entry point to mainline exit point without leaving the facility or stopping for reasons unrelated to traffic conditions.

Travel time distribution – The distribution of average facility travel times by analysis period across the reliability reporting period.

Travel time index – The ratio of actual travel time to a target travel time (e.g., the free-flow travel time, or a desirable travel time set by agency policy).

Travel time rate – The reciprocal of speed, expressed as time per unit distance traveled.

Travel time reliability – **1.** The probability of "on-time" arrival (i.e., the probability that a trip is completed below a certain threshold time). **2.** The variability in travel time for a given trip due to unforeseen causes such as variations in demand or an incident.

Truck – A heavy vehicle engaged primarily in the transport of goods and materials or in the delivery of services other than public transportation. See also *single-unit trucks* and *tractor trailers*.

Truck mode – A submode of the motorized vehicle mode in which single-unit trucks and tractor trailers operate along roadways.

Turn bay spillback – A condition under which a queue of turning vehicles exceeds the turn bay storage and spills back into the adjacent lane that is used by other vehicular movements.

Turning movement – The direction taken by a vehicle when it moves from one roadway to another at an intersection (i.e., left turn, right turn, U-turn). See also *movement*.

Turn lane – See *exclusive turn lane*.

Turnout – A short segment of a lane—usually a widened, unobstructed shoulder area—added to a two-lane, two-way highway, allowing slow-moving vehicles to leave the main roadway and stop so that faster vehicles can pass.

Two-lane highway – A roadway that generally has a two-lane cross section, one lane for each direction of flow, although passing and climbing lanes may be provided periodically. Within the two-lane sections, passing maneuvers must be made in the opposing lane.

Two-phase pattern – A type of operation at an all-way STOP-controlled intersection where drivers from opposing approaches enter the intersection at roughly the same time.

Two-sided weaving segment – A weaving segment in which at least one weaving maneuver requires three or more lane changes to be completed successfully or in which a single-lane on-ramp is closely followed by a single-lane off-ramp on the opposite side of the freeway.

Two-stage crossing – A condition that arises when a raised median refuge island is available, allowing pedestrians to cross one conflicting traffic stream at a time.

Two-stage gap acceptance – A condition where a median refuge area is available for minor-street through and left-turning drivers at a two-way STOP-controlled intersection so that drivers sequentially evaluate and use gaps in the near-side major-street traffic stream, followed by gaps in the far-side major-street traffic stream.

Two-way left-turn lane – A lane in the median area that extends continuously along a street or highway and is marked to provide a deceleration and storage area, out of the through-traffic stream, for vehicles traveling in either direction to use in making left turns at intersections and driveways.

Two-way STOP-controlled – The type of traffic control at an intersection where drivers on the minor street or drivers turning left from the major street wait for a gap in the major-street traffic to complete a maneuver.

U

Uncertainty – The range within which a model's estimate of a value is statistically likely to vary from the actual value.

Uncontrolled – Lacking a traffic control device that interrupts traffic flow (e.g., a traffic signal, STOP sign, or YIELD sign).

Undersaturated flow – Traffic flow where (*a*) the arrival flow rate is lower than the capacity of a point or segment, (*b*) no residual queue remains from a prior breakdown of the facility, and (*c*) traffic flow is unaffected by downstream conditions.

Undivided highway – A highway where opposing directions of travel are separated by paint stripes or painted buffers.

Undivided median type – An urban street where opposing directions of travel are not separated by a nonrestrictive median (e.g., two-way left-turn lane) or a restrictive median (e.g., raised curb).

Uniform delay – The first term of the equation for lane group control delay, assuming constant arrival and departure rates during a given time period.

Uninterrupted-flow facilities – Facilities that have no fixed causes of delay or interruption external to the traffic stream; examples include freeways and unsignalized sections of multilane and two-lane rural highways.

Unit extension – See *passage time*.

Unit width flow rate – The pedestrian flow rate expressed as pedestrians per minute per unit of walkway or crosswalk width.

Unmet demand – The number of vehicles on a signalized lane group that have not been served at any point in time as a result of operation in which demand exceeds capacity in either the current or the previous analysis period. This does not include the normal cyclical queue formation on the red and discharge on the green phase. See also *initial queue* and *residual queue.*

Unsignalized intersection – An intersection not controlled by traffic signals.

Upstream – The direction from which traffic is flowing.

Urban – **1.** An area typified by high densities of development or concentrations of population, drawing people from several areas within a region. **2.** A location within an urbanized area boundary, as defined by the Federal Highway Administration.

Urban street – A street with a relatively high density of driveway and cross-street access, located in an urban area, with traffic signals or interrupting STOP or YIELD signs no farther than 2 mi apart. HCM procedures are typically applicable to arterial and collector urban streets, including those in downtown areas.

Urban street facility – A length of roadway that is composed of contiguous urban street segments.

Urban street segment – A length of urban street from one boundary intersection to the next, including the upstream boundary intersection but not the downstream boundary intersection.

User group – See *mode group.*

User perception variability – Variation in user responses that occurs when different users experiencing identical conditions are asked to rate the conditions.

Utility – A measure of the value a traveler places on a trip choice.

V

Validation – The process by which the analyst checks the overall model-predicted traffic performance for a street–road system against field measurements of traffic performance, on the basis of field data not used in the calibration process.

Value pricing – See *congestion pricing.*

Variability – The day-to-day variation in congestion.

Vehicle – Any device in, on, or by which any person or property can be transported or drawn on a highway.

Vehicle capacity – The maximum number of vehicles that can pass a given point during a specified period under prevailing roadway, traffic, and control conditions.

Vehicle trajectory analysis – The development of performance measures from the properties of time–space trajectories of individual vehicles.

Verification – The process by which a software developer and other researchers check the accuracy of a software implementation of traffic operations theory.

Volume – The total number of vehicles or other roadway users that pass over a given point or section of a lane or roadway during a given time interval, often 1 h.

Volume balance – A condition in which the combined volume from all movements entering a segment equals the combined volume exiting the segment, in a given direction of travel.

Volume-to-capacity (v/c) ratio – The ratio of flow rate to capacity for a system element.

W

Walk interval – A period of time intended to give pedestrians adequate time to perceive the WALK indication and depart the curb before the pedestrian clear interval begins.

Walkways – Paved paths, ramps, and plazas that are generally located more than 35 ft from an urban street, as well as streets reserved for pedestrian traffic on a full- or part-time basis.

Wave speed – The speed at which a shock wave travels upstream or downstream through traffic.

Weaving – The crossing of two or more traffic streams traveling in the same direction along a significant length of highway, without the aid of traffic control devices (except for guide signs).

Weaving configuration – The linkage between the entry and exit lanes in a weaving segment, which determines lane-changing characteristics.

Weaving flow – The traffic movements in a weaving segment that are engaged in weaving movements.

Weaving length – See *base length, maximum weaving length,* and *short length.*

Weaving movement – A traffic flow within a weaving segment (on-ramp to mainline or mainline to off-ramp) that must cross paths with another traffic flow while traversing the segment.

Weaving segment – See *freeway weaving segment.*

Weaving segment influence area – See *influence area.*

Weaving segment width – The total number of lanes between the entry and exit gore areas within a weaving segment, including auxiliary lanes, if present.

Weight-to-power ratio – A truck's gross vehicle weight divided by the power produced by its engine; this ratio relates to a truck's ability to accelerate and to maintain a given speed on an upgrade.

Work zone – A segment of highway in which maintenance or construction operations reduce the number of lanes available to traffic or affect the operational characteristics of traffic flowing through the segment.

Y

Yellow change interval – The interval following the green interval, used to warn drivers of the impending red indication. A yellow indication is displayed for this duration.

Yellow time – The duration of the yellow change interval.

Yellow trap – A condition that leads a left-turning driver into the intersection believing the opposing driver is seeing a yellow indication.

Yield point – The earliest point in a coordinated signal operation that the controller can decide to terminate the coordinated phase(s).

2. LIST OF SYMBOLS

This section lists and defines the symbols used in HCM equations, along with their units if applicable. If a symbol has more than one meaning, the chapter or chapters of the specific use are cited in parentheses after the definition. Variations of symbols using the subscripts *i*, *j*, *k*, and *m* to indicate index values (e.g., segment *i*, lane group *j*, movement *m*) are generally not included; refer to the parent symbol in these cases for the definition and units.

$\%HV$ percentage of heavy vehicles (%)

$\%LL$ percentage of entry traffic using the left lane (decimal)

$\%OHP$ percentage of segment with occupied on-highway parking (decimal)

$\%RL$ percentage of entry traffic using the right lane (decimal)

$\%VL_i$ percentage of traffic present in lane L_i (decimal)

$\%VL_{i,DDI}$ percentage of traffic present in lane L_i for a DDI (decimal)

$\%VL_{max}$ percentage of the total approach flow in the lane with the highest volume (decimal)

2-to-1 indicator variable that is 1 when the work zone has a 2-to-1 configuration and 0 otherwise

2-to-2 indicator variable that is 1 when the work zone has a 2-to-2 configuration and 0 otherwise

3-to-2 indicator variable that is 1 when the work zone has a 3-to-2 configuration and 0 otherwise

4-to-3 indicator variable that is 1 when the work zone has a 4-to-3 configuration and 0 otherwise

a exponent calibration parameter (decimal, Chapter 12); PTSF coefficient for estimating BPTSF (Chapter 15); adjustment factor (Chapter 20); delay due to deceleration into a turn and acceleration after the next turn (s, Chapter 23)

A roundabout capacity model intercept (Chapter 22); parameter for the undersaturated model (Chapter 25); critical flow ratio for the arterial movements (Chapter 34)

a_1 passenger load weighting factor (Chapter 18); lane utilization model coefficient (Chapter 23)

a_2 lane utilization model coefficient

A_2 speed reduction per unit of flow rate in the curvilinear section of the speed–flow curve (mi/h)

A_2^{55} calibration factor for a free-flow speed of 55 mi/h (mi/h)

a_3 lane utilization model coefficient

$AADT$ annual average daily traffic (veh/day)

ACR facility AADT divided by its two-way hourly capacity

$AdjP(i)$ probability adjustment factor for degree-of-conflict case i

A_i expected passings per minute of mode i by average bicyclist

A_{I} critical flow ratio for the arterial movements for Intersection I

$A_{\text{I,II}}$ critical flow ratio for the arterial movements for the interchange

A_{II} critical flow ratio for the arterial movements for Intersection II

a_j indicator variable that is 1 when a vehicle is present in the lane and 0 otherwise

A_p pedestrian space (ft^2/p)

$A_{p,F}$ pedestrian space for the facility (ft^2/p)

A_{pbT} unoccupied time

A_T expected active passings per minute by the average bicycle during the peak 15 min

ATS_d average travel speed in the analysis direction (mi/h)

ATS_F average travel speed for the facility (mi/h)

ATS_i average travel speed for directional segment *i* (mi/h)

ATS_{pl} average travel speed in the analysis segment as affected by a passing lane (mi/h)

$AuxLength$ auxiliary lane length (ft)

$AveCap(s)$ average capacity per lane for section *s* (veh/h/ln)

AVO_i average vehicle occupancy on segment *i* (p/veh)

a_w approach lane width during work zone (= total width of all open left-turn, through, and right-turn lanes) (ft)

b PTSF coefficient for estimating BPTSF (Chapter 15); intermediate calculation variable (Chapter 30)

B roundabout capacity model coefficient (Chapter 22); parameter for the undersaturated model (Chapter 25)

$b_{d,j}$ destination adjustment factor *j*

$BFFS$ base free-flow speed (mi/h)

b_i bunching factor for lane group *i*

$b_{i,j,k}$ proportion of volume at destination *j* that came from origin *i* for subperiod *k* (veh/h)

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

$BLOS$ bicycle level-of-service score

$b_{o,i}$ origin adjustment factor *i*

BP breakpoint in the speed–flow curve separating the linear and curvilinear sections (pc/h/ln)

BP_{75} breakpoint for a free-flow speed of 75 mi/h (pc/h/ln)

BP_{ao} breakpoint in the automobile-only flow condition (pc/h/ln)

BP_{mix} breakpoint for mixed flow (veh/h/ln)

$BPTSF_d$ base percent time-spent-following in the analysis direction

c base capacity (pc/h/ln, Chapter 12); capacity of the combined movements (veh/h, Chapter 30); intermediate calculation variable (Chapter 30)

C cycle length (s, Chapter 19); parameter for the undersaturated model (Chapter 25)

C' cycle length (steps)

c_{75} managed lane capacity for a free-flow speed of 75 mi/h (pc/h/ln);

c_a available capacity for a lane group served by an actuated phase (veh/h)

c_A average capacity (veh/h)

$c_{a,l,e}$ available capacity of an exclusive-lane lane group with permitted left-turn operation (veh/h)

$c_{a,l,e,p}$ available capacity of an exclusive-lane lane group with protected left-turn operation (veh/h)

$c_{a,l,e,pp}$ available capacity of an exclusive-lane lane group with protected–permitted left-turn operation (veh/h)

$c_{a,r,e,pp}$ available capacity of an exclusive-lane lane group with protected–permitted right-turn operation (veh/h)

$c_{a,sl}$ available capacity of a shared-lane lane group with permitted left-turn operation (veh/h)

$c_{a,sl,pp}$ available capacity of a shared-lane lane group with protected–permitted left-turn operation (veh/h)

c_{adj} adjusted segment capacity (pc/h/ln)

CAF capacity adjustment factor (unitless)

CAF_{ao} capacity adjustment factor for the automobile-only case (e.g., due to weather or incidents) (decimal)

CAF_{cal} capacity adjustment factor for calibration purposes (unitless)

$CAF_{g,mix}$ capacity adjustment factor for grade in mixed-flow conditions (decimal)

CAF_{mix} mixed-flow capacity adjustment factor for the basic freeway segment (decimal)

$CAF_{T,mix}$ capacity adjustment factor for the percentage of trucks in mixed-flow conditions (decimal)

CAF_{weave} capacity adjustment factor for a weaving segment (decimal)
CAF_{wz} capacity adjustment factor for a work zone (decimal)
C_{ao} base segment capacity (pc/h/ln)
$CapMFlanes(s)$ capacity per mixed-flow lane in section s (veh/h/ln)
$CapShldr(s)$ capacity per shoulder lane for section s (veh/h/ln)
c_b capacity of the bicycle lane (bicycles/h, Chapter 19); capacity during the blocked regime (veh/h, Chapter 23)
$c_{bypass,pce}$ capacity of the bypass lane, adjusted for heavy vehicles (pc/h)
$c_{d,j,k}$ capacity at the downstream intersection for movement j for subperiod k (veh/h)
c_{dATS} capacity in the analysis direction under prevailing conditions based on ATS (pc/h)
c_{dPTSF} capacity in the analysis direction under prevailing conditions based on PTSF (pc/h)
C_e equilibrium cycle length (s)
$c_{e,L,pce}$ capacity of the left entry lane, adjusted for heavy vehicles (pc/h)
$c_{e,pce}$ lane capacity, adjusted for heavy vehicles (pc/h)
$c_{e,R,pce}$ capacity of the right entry lane, adjusted for heavy vehicles (pc/h)
$CFAF_{int}$ crash frequency adjustment factor for an intersection
$CFAF_{rf}$ crash frequency adjustment factor for rainfall
$CFAF_{seg}$ crash frequency adjustment factor for a segment
$CFAF_{sf}$ crash frequency adjustment factor for snowfall
$CFAF_{sp}$ crash frequency adjustment factor for snow or ice on pavement (not snowing)
$CFAF_{wea}$ crash frequency adjustment factor for weather condition *wea*
$CFAF_{wp}$ crash frequency adjustment factor for wet pavement (not raining)
c_{GA} capacity during the gap acceptance regime (veh/h)
CG_{DS} common green time with demand starvation potential (s)
c_{GP} unadjusted capacity of the general purpose lanes (veh/h)
c_{GPA} adjusted capacity of the general purpose lanes (veh/h)
CG_{RD} common green time between the upstream ramp green and the downstream arterial through green (s)
CG_{UD} common green time between the upstream through green and downstream through green (s)
CG_{U_iD} common green time between upstream approach i and downstream through green (s)
ci set of critical phases on the critical path
c_i capacity of lane, lane group, or section i (veh/h); movement capacity during iteration i (veh/h, Chapter 30)
$c_{i,PCE}$ capacity for lane i (pc/h)
c_{I} movement capacity for the Stage I process (veh/h)
c_I intersection capacity (tpc/h/ln)
$CI_{1-\alpha}$ confidence interval for the true average value, with a level of confidence of $1 - \alpha$
CID central island diameter (ft)
c_{IFL} capacity of a basic freeway segment with the same free-flow speed as the weaving segment under equivalent ideal conditions, per lane (pc/h/ln)
c_{II} movement capacity for the Stage II process (veh/h)
c_{IW} capacity of all lanes in the weaving segment under ideal conditions (pc/h)
c_{IWL} capacity of the weaving segment under equivalent ideal conditions (pc/h/ln)
c_l capacity of a left-turn movement with permitted left-turn operation (veh/h)
CL indicator variable that is 1 when the trail has a centerline and 0 otherwise
$c_{l,e}$ capacity of an exclusive-lane lane group with permitted left-turn operation (veh/h)
$c_{l,e,p}$ capacity of an exclusive-lane lane group with protected left-turn operation (veh/h)
$c_{l,e,pp}$ capacity of an exclusive-lane lane group with protected–permitted left-turn operation (veh/h)
c_{L+TH} capacity of the through and left-turn movements (veh/h)

CM capacity of downstream section (veh/h)
$c_{m,j}$ capacity of movement j
$c_{m,x}$ capacity of movement x (veh/h)
$c_{m,y}$ movement capacity of the y movement in the subject shared lane (veh/h)
c_{md} unadjusted capacity of merge/diverge area (veh/h)
c_{mda} adjusted capacity of merge/diverge area (veh/h)
c_{mg} merge capacity (veh/h)
$C_{mix,j}$ mixed-flow capacity for segment j (veh/h/ln)
c_{ms} midsegment capacity (veh/h)
C_{NCF} capacity of Regime 3 with no conflicting flow rate (veh/h)
c_{nm} nonmerge capacity for the inside lane (veh/h)
CP change period (yellow change interval plus red clearance interval) (s)
$c_{p,x}$ potential capacity of movement x (veh/h)
c_{pce} lane capacity adjusted for heavy vehicles (pc/h)
c_{q1r} shared lane capacity for upstream right-turn traffic movement (veh/h)
c_R actual capacity of the flared lane (veh/h)
CR crash rate per 100 million vehicle miles traveled
$c_{r,e,pp}$ capacity of an exclusive-lane lane group with protected–permitted right-turn operation (veh/h)
$c_{r,x}$ capacity of movement x assuming random flow during the unblocked period (veh/h)
CRF capacity reduction factor (decimal)
c_s saturated capacity (veh/h)
c_{sep} sum of the capacity of the right-turning traffic operating as a separate lane and the capacity of the other traffic in the right lane (upstream of the flare) operating in a separate lane (veh/h)
c_{SH} capacity of the shared lane (veh/h)
c_{sl} capacity of a shared-lane lane group with permitted left-turn operation (veh/h)
$c_{sl,pp}$ capacity of a shared-lane lane group with protected–permitted left-turn operation (veh/h)
c_{sum} intersection capacity (tpc/h/ln)
c_T total capacity for the subject movement
c_{th} through-movement capacity (veh/h)
c_{thru} capacity for the exiting through movement (veh/h)
c_{total} total capacity of a work zone (pc/h)
c_{turn} capacity for the exiting turn movement (veh/h)
$c_{u,i,k}$ capacity at the upstream intersection for movement i for subperiod k (veh/h)
c_w unadjusted capacity of weaving area (veh/h)
CW cross-weave demand flow rate (pc/h)
c_{wa} adjusted capacity of weaving area (veh/h)
c_{wz} work zone capacity (prebreakdown flow rate) (pc/h/ln)
c_{YCT} combined capacity of the YIELD-controlled turn (veh/h)
d demand flow rate (veh/h, Chapter 10) (pc/h, Chapter 12); control delay (s/veh, Chapters 19 and 20); grade length (mi, Chapter 25)
D proportion of peak-hour traffic in the peak direction (decimal, Chapter 3); density (pc/mi/ln, Chapter 12); distance between the two intersections of the interchange (ft, Chapter 22); distance from the ramp movement stop bar to the conflict point (ft) measured along the centerline of the off-ramp approach (Chapter 23); intermediate calculation result (Chapter 24); parameter for the undersaturated model (Chapter 25)
d_1 uniform delay (s/veh, Chapter 19); conditional delay to first through vehicle (s/veh, Chapter 30)
$d_{1,agg,i,j,all}$ aggregated uniform delay for lane group j at intersection i for all subperiods (s/veh)
$d_{1,i}$ average uniform delay in direction i (s/pc)

$D_{1,i}$ total directional uniform control delay per cycle (s)

d_{1b} baseline uniform delay (s/veh)

d_2 incremental delay (s/veh, Chapter 19); conditional delay to Vehicle 2 (s/veh, Chapter 30)

$d_{2,d}$ average deterministic delay per vehicle (s/veh)

d_3 initial queue delay (s/veh)

d_A control delay on the approach (s/veh)

d_a acceleration/deceleration delay (s)

D_a access point density on segment (points/mi)

$D_{a,j}$ adjusted volume for destination j (veh/h)

$d_{A,j}$ approach control delay for approach j (s/veh)

$D_{A,j,k}$ adjusted volume for destination j for subperiod k (veh/h)

$d_{A,x}$ control delay on approach x (s/veh)

d_{ad} transit vehicle acceleration/deceleration delay due to a transit stop (s/veh)

DAF_{cal} demand adjustment factor for calibration purposes

$DAF_s(tp, seg)$ demand adjustment factor for scenario s, period tp, and segment seg

$d_{ap,i}$ delay due to left and right turns from the street into access point intersection i (s/veh)

$d_{ap,l}$ through vehicle delay due to left turns (s/veh)

$d_{ap,r}$ through vehicle delay due to right turns (s/veh)

d_b bicycle delay (s/bicycle)

d_{bypass} control delay for the right-turn bypass lane (s/veh)

D_c density at capacity (pc/mi/ln, Chapter 12); distance to nearest signal-controlled crossing (ft, Chapter 18)

$d_{control}$ through control delay (s/veh)

DC_s demand combination associated with scenario s

D_d diversion distance (ft)

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

$DDHV$ directional design-hour volume (veh/h)

$DEF(i, t, p)$ deficit: unmet demand from a previous time interval p that flows past node i during time step t

D_f distance from the U-turn crossover to the main junction (ft)

D_F average density for the facility (pc/mi/ln)

d_g average pedestrian gap delay (s)

d_{gd} average gap delay for pedestrians who incur nonzero delay

d_{geom} geometric delay (s/veh)

$D_{GP,vert}$ delay incurred by vehicles originating from the general purpose lanes waiting in the vertical queue for one 15-min analysis period (h)

d_i vehicle demand on segment i (veh, Chapter 2) ; control delay for lane i (s/veh, Chapter 19); conditional delay to vehicle i (i = 3, 4, . . . ,) (s/veh, Chapter 30)

di incident duration (h)

$\overline{di}$ average incident duration (h)

D_i person-hours of delay on segment i (Chapter 2); density for segment i (pc/mi/ln, Chapter 10)

d_I intersection control delay (s/veh)

$d_{i,t}$ demand on section i in analysis period t (pc/mi)

$D_{i,t}$ density on section i in analysis period t (pc/mi)

$d'_{i,t-1}$ carryover demand on section i at analysis period t

$d_{intersection}$ control delay for the entire intersection (s/veh)

d_j control delay for movement j (s/veh, Chapter 23); length of segment j (mi, Chapter 25)

D_j volume for destination j (veh/h)

d_l control delay for the left-turn movement (s/veh)

d_{LL} control delay in left lane (s/veh)

$d_{M,LT}$ delay to major-street left-turning vehicles (s/veh)

$DM(s)$ demand multiplier associated with scenario s

$DM(Seed)$ demand multiplier associated with the seed file

D_{MD} density in the major diverge influence area (which includes all approaching freeway lanes) (pc/mi/ln)

d_{mg} merge delay (s/veh)

d_{mile} average delay per mile (s/veh)

$\overline{DM}_j$ weighted average demand multiplier for all days in month j relative to seed value

$D_{ML,vert}$ delay incurred by vehicles originating from the managed lanes waiting in the vertical queue for one 15-min analysis period (h)

d_{nm} nonmerge delay for the inside lane (s/veh)

d_{oa} overall distance, the summation of all the segment grade lengths on the composite grade (mi)

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

d_{other} delay due to other sources along the segment (s/veh)

D_p phase duration (s)

d_p average pedestrian delay (s)

DP delayed passings factor

$D_{p,a}$ phase duration for phase a, which occurs just before phase b (s)

$D_{p,b}$ phase duration for phase b, which occurs just after phase a (s)

$d_{p,d}$ pedestrian delay in traversing Crosswalk D (s/p)

$D_{p,l}$ phase duration for left-turn phase l (s)

$D_{p,mi}$ duration of the phase serving the minor-street through movement (s)

$D_{p,t}$ phase duration for coordinated phase t (s)

d_{pc} pedestrian delay in crossing the segment at a signalized intersection (s/p)

d_{pd} pedestrian diversion delay (s/p)

D_{ped} pedestrian density (p/ft²)

DP_m delayed passings per minute

d_{pp} pedestrian delay incurred in walking parallel to the segment (s/p)

d_{ps} transit vehicle delay due to serving passengers (s)

d_{pw} pedestrian waiting delay (s/p)

d_{px} crossing delay (s/p)

DQ_A distance to the downstream queue at the beginning of the upstream arterial green (ft)

DQ_i distance to the downstream queue at the beginning of the upstream green for approach i (ft)

DQ_R distance to the downstream queue at the beginning of the upstream ramp green (ft)

D_R density in the ramp influence area (pc/mi/ln)

d_r control delay for the right-turn movement (s/veh)

d_{Rank1} delay to Rank 1 vehicles (s/veh)

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

d_{re} transit vehicle reentry delay (s/veh)

d_{RL} control delay in right lane (s/veh)

D_S speed index for off-ramps

d_s saturated uniform delay (s/veh)

d_{sep} control delay for the movement considered as a separate lane

d_{signal} average delay per signal (s/veh)

d_{sl} delay in shared left-turn and through lane group (s/veh)

D_{SP} duration of study period (h)

d_{sr} delay in shared right-turn and through lane group (s/veh)

DSV daily service volume (veh/day)

D_{sv} distance between stored vehicles (ft)

DSV_i daily service volume for level-of-service i (veh/day)

d_t control delay for the through movement (s/veh, Chapters 18 and 20); time step duration (s/step, Chapters 23 and 30)

D_t distance traveled along the loop ramp or diverted movement (ft, Chapter 23); distance from the main junction to the U-turn crossover (ft, Chapter 23)

$d_{t,1}$ average delay to through vehicles in the inside lane (s/veh)

d_{tlr} through vehicle delay per right-turn maneuver (s/veh)

d_{th} delay in exclusive through-lane group (s/veh)

d_{trip} average delay per trip (s/veh)

d_{ts} delay due to a transit vehicle stop

D_{up} unbalanced phase duration (s)

$D_{up,i}$ unbalanced phase duration for phase i (s)

d_{vq} time-in-queue per vehicle (s/veh)

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

$dv_{u,i,k}$ maximum discharge rate for upstream movement i for subperiod k (veh/h)

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

dx_j length of discrete segment j (mi)

e ridership elasticity with respect to changes in the travel time rate (Chapter 18); extension of effective green time (s, Chapter 19)

E weighted events per minute (Chapter 24); parameter for the undersaturated model (Chapter 25)

$E[n_w, j]$ expected frequency of weather event w in month j, rounded to the nearest integer

$E_{15min}[D_w]$ expected duration of weather event w, rounded to the nearest 15-min increment

$ED(i, p)$ expected demand (veh/h) that would arrive at segment i on the basis of upstream conditions over time interval p

$EDTT$ extra distance travel time (s)

E_{HV} equivalency factor for heavy vehicles

E_L equivalent number of through cars for a protected left-turning vehicle

$E_{L,m}$ modified through-car equivalent for a protected left-turning vehicle

E_{L1} equivalent number of through cars for a permitted left-turning vehicle

$E_{L1,m}$ modified through-car equivalent for a permitted left-turning vehicle

E_{L2} equivalent number of through cars for a permitted left-turning vehicle when opposed by a queue on a single-lane approach

$E_{L2,m}$ modified through-car equivalent for a permitted left-turning vehicle when opposed by a queue on a single-lane approach

E_{LT} equivalency factor for left turns

$E_{LT,pm}$ equivalency factor for permitted left-turn operation

$E_{LT,pt}$ equivalency factor for protected left-turn operation

E_{LU} equivalency factor for lane utilization

E_{other} equivalency factor for other conditions

e_p permitted extension of effective green (s)

E_p equivalency factor for parking activity

E_{PHF} equivalency factor for peaking characteristics

E_R passenger car equivalent for recreational vehicles (Chapter 15); equivalent number of through cars for a protected right-turning vehicle (Chapter 19)

$E_{R,ap}$ equivalent number of through cars for a protected right-turning vehicle at an access point

$E_{R,m}$ modified through-car equivalent for a protected right-turning vehicle

E_{RT} equivalency factor for right turns

E_T passenger car equivalent of one heavy vehicle in the traffic stream

E_{TC} passenger car equivalent for trucks operating at crawl speed

ETT experienced travel time (s/veh)

ETT_A approach experienced travel time (s/veh)

ETT_{DLT} weighted average experienced travel time for the DLT intersection (s/veh)

ETT_I intersection experienced travel time (s/veh)

F total events on the path (events/h, Chapter 24); smoothing factor (Chapter 30)

$F(x)$ cumulative probability of a normal distribution of speeds with mean μ and standard deviation σ

f_{12} capacity adjustment factor for Rank 2 minor-street right-turn Movement 12

f_{1U} capacity adjustment factor for Rank 2 major-street U-turn Movement 1

f_{4U} capacity adjustment factor for Rank 2 major-street U-turn Movement 4

f_9 capacity adjustment factor for Rank 2 minor-street right-turn Movement 9

f_a adjustment factor for area type

f_A adjustment for access point density (mi/h)

f_{ad} proportion of transit vehicle stop acceleration/deceleration delay not due to traffic control

f_{ap} access point volume adjustment factor

f_{AT} indicator variable for area type that is 1 for rural areas and 0 otherwise

f_b buffer area coefficient

$f_{B\%}$ percentile back-of-queue factor

f_{bb} adjustment factor for blocking effect of local buses that stop within intersection area

f_{Br} indicator variable for barrier type that is 1 for cone, plastic drum, or other soft barrier separation and 0 otherwise

F_c unsignalized conflicts factor

$f_{c,dry}$ hourly crash frequency for dry pavement

$f_{c,wea}$ hourly crash frequency for weather condition *wea*

F_{cd} roadway crossing difficulty factor

f_{CS} adjustment for cross section (mi/h)

$Fc_{str(i)}$ expected crash frequency for street location *i* of type *str* (crashes/year)

$Fc_{str(i),dry}$ equivalent crash frequency when every day is dry for street location *i* of type *str*

$Fc_{str(i),wea}$ equivalent crash frequency when every day has weather condition *wea*

f_{DDI} adjustment for DDI crossover

F_{delay} pedestrian delay adjustment factor

f_{DN} indicator variable for daylight or night that is 1 for night and 0 for daylight

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

$f_{dow,input}$ day-of-week adjustment factor for day associated with v_{input}

f_{dt} proportion of dwell time occurring during effective green

FFS free-flow speed (mi/h)

FFS_{adj} adjusted free-flow speed (mi/h)

FFS_{mix} mixed-flow free-flow speed (mi/h)

FFS_{wz} work zone free-flow speed (mi/h)

$f_{g,ATS}$ grade adjustment factor for ATS determination

$f_{g,PTSF}$ grade adjustment factor for PTSF determination

F_h headway factor

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

$f_{hod,input}$ hour-of-day adjustment factor for hour and day associated with v_{input}

f_{HV} heavy vehicle adjustment factor

$f_{HV,ATS}$ heavy vehicle adjustment factor for average travel speed

$f_{HV,e}$ heavy vehicle adjustment factor for the entry lane

$f_{HV,i}$ heavy vehicle adjustment factor for movement *i*

$f_{HV,PTSF}$ heavy vehicle adjustment factor for PTSF determination

f_{HVg} adjustment factor for heavy vehicles and grade

F_i frequency with which mode *i* will block two lanes

$f_{ic,int(i),n,m,ap,d}$ saturation flow adjustment factor for incident presence for movement *m* on leg associated with NEMA phase *n* at intersection *i* during analysis period *ap* and day *d*

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

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

$Fi_{str(i),wea(h,d)}$ expected incident frequency for street location *i* of type *str* and weather condition *wea*(*h*, *d*) during hour *h* and day *d* (incidents/year)

f_j capacity adjustment factor for Movements 9 and 12

f_{jU} capacity adjustment factor for Movements 1U and 4U

f_k capacity adjustment factor for all Rank 3 movements

f_l capacity adjustment factor for all Rank 4 movements

f_L signal spacing (boundary intersection) adjustment factor

F_l passenger load factor (passengers/seat)

f_{LAT} lateral distance from the edge of travel lane adjacent to the work zone to the barrier, barricades, or cones (ft)

f_{LC} adjustment for lateral clearance (mi/h)

f_{Lpb} pedestrian adjustment factor for left-turn groups

f_{LS} adjustment for lane and shoulder width (mi/h)

f_{LT} adjustment factor for left-turn vehicle presence in a lane group

f_{LU} adjustment factor for lane utilization

f_{LW} adjustment for lane width (mi/h)

f_M adjustment for median type (mi/h)

F_m number of meeting events (events/h)

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

$f_{moy,input}$ month-of-year adjustment factor for day associated with v_{input}

f_{ms} adjustment factor for downstream lane blockage

$f_{np,ATS}$ adjustment factor for ATS determination for the percentage of no-passing zones in the analysis direction

$f_{np,PTSF}$ adjustment to PTSF for the percentage of no-passing zones in the analysis segment

FO_4 force-off point for Phase 4 (s)

f_p adjustment factor for existence of a parking lane and parking activity adjacent to lane group

F_p number of passing events (events/h)

F_p pavement condition adjustment factor

$f_{p,l}$ capacity adjustment factor for the Rank 4 minor-street left-turn movement

f_{pb} pedestrian blockage factor for the proportion of time that one lane on an approach is blocked during 1 h

f_{ped} entry capacity adjustment factor for pedestrians

f_{pk} adjustment for on-street parking (mi/h)

$f_{pl,ATS}$ adjustment factor for the effect of passing lane on average travel speed

$f_{pl,PTSF}$ adjustment factor for the impact of a passing lane on percent time-spent-following

f_R adjustment factor for the effects of travel path radius

f_{reduce} adjustment factor for reducing lanes during work zone presence

f_{RLC} adjustment for right-side lateral clearance

f_{Rpb} pedestrian–bicycle adjustment factor for right-turn groups

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

f_{RT} adjustment for right-turning vehicle presence in the lane group

F_S motorized vehicle speed adjustment factor

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

f_{sp} adjustment factor for sustained spillback

$f_{sp,i,k,l}$ adjustment factor for spillback for upstream movement *i* for iteration *l* in subperiod *k*

$f_{speed,i}$ ATS adjustment for direction *i* (decimal)

f_{Sr} speed ratio (decimal); the ratio of non–work zone speed limit (before the work zone was established) to work zone speed limit

f_{sw} sidewalk width coefficient

f_{tg} traffic growth factor

f_{TISi} time-interval scale factor for time period *i*

f_{TLC} adjustment for total lateral clearance

F_{tt} perceived travel time factor

f_v adjustment factor for traffic pressure or proximity

F_v motorized vehicle volume adjustment factor

f_w adjustment factor for lane width

F_w cross-section adjustment factor

f_{wid} adjustment factor for approach width

f_{wz} adjustment factor for work zone presence at the intersection

f_x control-type adjustment factor

$fx_{i,2,k}$ volume adjustment factor for origin *i* for subperiod *k*

g effective green time (s)

$\mathcal{G}_i$ set of incidents of severity type *i*

G percentage grade (Chapter 20); green interval duration (s, Chapter 19)

$\mathbb{G}(i)$ distribution function for incident with severity type *i*

$G_{1|ped,call}$ average green interval given that the phase is called by a pedestrian detection (s)

$G_{1|veh,call}$ average green interval given that the phase is called by a vehicle detection (s)

g' effective green time adjusted for the presence of a downstream queue or for demand starvation (s)

G_3 green interval duration for Phase 3 (s)

g_a available effective green time (s)

G_A green interval for the external arterial approach (s)

g_b effective green time for the bicycle lane (s)

$g_{c,i}$ effective green time for critical lane group *i* (s)

G_D green interval for the downstream arterial through movement (s)

g_{diff} supplemental service time for shared single-lane approaches (s)

g_e green extension time (s)

g_f time before the first left-turning vehicle arrives and blocks the shared lane (s)

$g_{f,max}$ maximum time before the first left-turning vehicle arrives and within which there are sufficient through vehicles to depart at saturation (s)

g_i effective green time for lane group *i* (s)

G_i effective green time for direction *i* (s)

$G_{i,min}$ minimum effective green time for direction *i* (s)

g_j grade of segment *j* (decimal)

g_l effective green time for left-turn phase (s)

$g_{lt,pm}$ effective green time for permitted left-turn operation during the through phase (s)

$g_{lt,pt}$ effective green time for the protected left-turn phase (s)

G_{max} maximum green setting (s)

$G_{max,r}$ maximum green setting for the phase serving the subject right-turn movement during its permitted period (s)

G_{min} minimum green setting (s)

G_{opt} optimal effective green time for one direction (s)

g_p effective green time for permitted left-turn operation (s)

G_p displayed green interval corresponding to g_p (s)

$G_{p,min}$ minimum green interval duration based on pedestrian crossing time (s)

g_{ped} pedestrian service time (s)

g_{ps} queue service time during permitted left-turn operation (s)

g_q opposing queue service time (s)

G_q displayed green interval corresponding to g_q (s)

G_R green interval for the left-turning ramp movement (s)

g_s queue service time (s)

g_{tot} total effective green time in the cycle (s)

g_u duration of permitted left-turn green time that is not blocked by an opposing queue (s)

G_u unbalanced green interval duration for a phase (s)

G_U displayed green interval corresponding to g_u (s)

g_u^* adjusted duration of permitted left-turn green time that is not blocked by an opposing queue (s)

G_{U_i} green interval for the upstream approach i (s)

$g_{\text{Walk},mi}$ effective walk time for the phase serving the minor-street movement (s)

h saturation headway (s, Chapter 4); full stop rate (stops/veh, Chapter 18); average headway for each through lane (s, Chapter 20); average call headway for all calls with headways less than MAH^* (s, Chapter 31)

$h_{i,\Delta<h<H1}$ average headway of those headways between Δ and H_1 (s/veh)

h_0 base saturation headway (s/pc)

h_1 deterministic stop rate (stops/veh)

H_1 maximum headway that the first through vehicle can have and still incur delay (s/veh)

h_{adj} headway adjustment (s)

h_{base} base saturation headway (s)

h_d departure headway or average time between departures of successive vehicles on a given approach (s)

H_F spatial stop rate for the facility (stops/mi)

$h_{HV,adj}$ headway adjustment for heavy vehicles (s)

$\hat{h}_i$ adjusted time headway for direction i (s)

h_I saturation headway for the internal through approach (s)

h_{is} saturation headway or time between departures of successive vehicles on a given approach for degree-of-conflict case i (s)

$h_{LT,adj}$ headway adjustment for left turns (s)

h_{other} full stop rate due to other sources (stops/veh)

$h_{RT,adj}$ headway adjustment for right turns (s)

h_{s1} saturation headway if no vehicle is waiting on the conflicting approach

h_{s2} saturation headway if the conflicting approach is occupied

H_{seg} spatial stop rate for the segment (stops/mi)

h_{si} saturation headway

h_T total stop rate (stops/veh)

HV percentage of heavy vehicles (decimal)

i crossing event index

I adjustment factor for type, intensity, and proximity of work activity (pc/h/ln, Chapter 10); upstream filtering adjustment factor (Chapter 19)

$I_{a,seg}$ automobile traveler perception score for the segment

$I_{b,f}$ bicycle LOS score for the facility

$I_{b,int}$ bicycle LOS score for the intersection

$I_{b,\text{link}}$ bicycle LOS score for the link

$I_{b,seg}$ bicycle LOS score for the segment

I_c indicator variable that is 0 when the density in the adjacent general purpose lane is less than or equal to 35 pc/mi/ln or the segment type is Buffer 2, Barrier 1, or Barrier 2; and 1 otherwise

ICD inscribed circle diameter (ft)

ICR incident-to-crash ratio

ID interchange density; the number of interchanges within ±3 mi of the center of the subject weaving segment divided by 6 (int/mi)

IDR incident delay rate (h/mi)

$I_{fi,int(i),n,ap,d}$ indicator variable that is 1 for fatal-or-injury crash on leg associated with NEMA phase *n* at intersection *i* during analysis period *ap* and day *d*, and 0 otherwise

I_{LC} lane-changing intensity (lc/ft)

I_{lt} indicator variable that is 1 when there is no left-turn bay on the major street at the access point and 0 otherwise

Inc_{Dur} incident duration (min)

Inc_{Type} incident severity type (1–5)

I_{night} indicator variable for night that is 0 if rain starts between 6:00 a.m. and 6:00 p.m. and 1 otherwise

Intercept model intercept

$I_{other,int(i),n,ap,d}$ indicator variable that is 1 for noncrash incident on leg associated with NEMA phase *n* at intersection *i* during analysis period *ap* and day *d*, and 0 otherwise

$I_{p,F}$ pedestrian LOS score for the facility

$I_{p,int}$ pedestrian LOS score for the intersection

$I_{p,link}$ pedestrian LOS score for the link

$I_{p,seg}$ pedestrian LOS score for the segment

$I_{pdo,int(i),n,ap,d}$ indicator variable that is 1 for property-damage-only crash on leg associated with NEMA phase *n* at intersection *i* during analysis period *ap* and day *d*, and 0 otherwise

I_{pk} indicator variable for on-street parking occupancy that is 1 with no occupied on-street parking and 0 otherwise

IR_j incident rate per 100 million vehicle miles traveled in month *j*

I_{rt} indicator variable that is 1 when there is no right-turn bay on the major street at the access point and 0 otherwise

I_s interval between vehicle-in-queue counts (s)

I_t indicator variable that is 1.0 when equations are used to evaluate delay due to left turns and 0.00001 when equations are used to evaluate delay due to right turns

$I_{t,F}$ transit LOS score for the facility

$I_{t,seg}$ transit LOS score for the segment

j time step associated with platoon arrival time t'

k incremental delay factor (Chapter 19); proportion of AADT occurring in the peak hour (decimal, Chapter 25)

K proportion of AADT occurring in the peak hour (decimal)

$K(i, p)$ average traffic density (veh/mi/ln) of segment *i* over time interval *p*

$K(NS, p)$ average vehicle density over the entire facility during time interval *p*

$K(NS, P)$ average vehicle density over the entire facility during the entire analysis period *P*

$KB(i, p)$ background density: segment *i* density (veh/mi/ln) over time interval *p* assuming there is no queuing on the segment

KC ideal density at capacity (veh/mi/ln)

K_c^f density at capacity, with the frictional effect of the adjacent general purpose lane (pc/mi/ln)

K_c^{nf} density at capacity, without the frictional effect of the adjacent general purpose lane (pc/mi/ln)

K_{GP} density of the adjacent general purpose lane (pc/mi/ln)

k_i density of users of mode *i* (users/mi)

K_I internal link density for arterial through movements (veh/mi)

KJ facilitywide jam density (veh/mi/ln)

k_{jam} jam density (veh/mi)

k_{min} minimum incremental delay factor

$k_{o,i}$ density of users of mode i in the opposing direction (users/mi)

$K_p(NS)$ average facility density in time interval p

$KQ(i, t, p)$ queue density: vehicle density (veh/mi/ln) in the queue on segment i during time step t in time interval p

$k_{s,i}$ density of users of mode i in the subject direction (users/mi)

l work zone length (ft)

L segment length (ft, Chapter 18); cycle lost time (s, Chapter 19); crosswalk length (ft, Chapter 20); design vehicle length (ft, Chapter 23); length of path segment (mi, Chapter 24); distance from midpoints of the upstream segment and the subject segment (ft, Chapter 25)

$L(d)$ length represented by detector station d (mi)

l_1 start-up lost time (s)

$l_{1,p}$ permitted start-up lost time (s)

l_2 clearance lost time (s)

L_a available queue storage distance (ft/ln)

L_A length of acceleration lane (ft)

$L_{a,lt}$ available queue storage distance for the left-turn movement (ft/ln)

$L_{a,thru}$ available queue storage distance for the through movement (ft/ln)

$L_{a,turn}$ available queue storage distance for the turn movement (ft/ln)

L_{A1} length of Acceleration Lane 1 (ft)

L_{A2} length of Acceleration Lane 2 (ft)

L_{Aeff} effective length of both acceleration lanes (ft)

LAG_{DLT} time duration between the reference point and the start of the displaced left-turn phase (s)

LAG_{TH} time duration between the reference point and the start of the major-street through phase (s)

L_B base length of the weaving segment, measured from the points at which the edges of the travel lanes of the merging and diverging roadways converge (ft)

LC_{ALL} total rate of lane changing of all vehicles within the weaving segment (lc/h)

L_{cc} curb-to-curb crossing distance (ft)

LC_{FR} minimum number of lane changes that a freeway-to-ramp weaving vehicle must make to complete the freeway-to-ramp movement successfully (lc)

LC_L left-side lateral clearance (ft)

LC_{MIN} minimum rate of lane changing that must exist for all weaving vehicles to complete their weaving maneuvers successfully (lc/h)

LC_{NW} total rate of lane changing by nonweaving vehicles within the weaving segment (lc/h)

LC_R right-side lateral clearance (ft)

LC_{RF} minimum number of lane changes that a ramp-to-freeway weaving vehicle must make to complete the ramp-to-freeway movement successfully (lc)

LC_{RR} minimum number of lane changes that must be made by one ramp-to-ramp vehicle to complete a weaving maneuver

$LCSI$ lane closure severity index

LC_W total rate of lane changing by weaving vehicles within the weaving segment (lc/h)

$L_{cw\text{-}max}$ distance from the gore to the end of the ML access segment (ft)

$L_{cw\text{-}min}$ distance between the on-ramp gore area and the beginning of the ML access segment (ft)

L_d length downstream of the passing lane beyond its effective length (mi, Chapter 15); length of Crosswalk D (ft, Chapter 19)

L_D length of deceleration lane (ft)

$L_{D\text{-}A}$ lost time on the external arterial approach due to the presence of downstream queue (s)

$L_{D\text{-}U_i}$ lost time on upstream approach i due to presence of a downstream queue (s)

L_{D1} length of Deceleration Lane 1 (ft)

L_{D2} length of Deceleration Lane 2 (ft)

L_{de} length downstream of the passing lane within its effective length (mi)

L_{Deff} effective length of both deceleration lanes (ft)

L'_{de} length downstream of the passing lane within the analysis segment (mi)

L_{DOWN} distance between the subject ramp junction and the adjacent downstream ramp junction (ft)

$L_{D\text{-}R}$ lost time on the external ramp approach due to the presence of downstream queue (s)

L_{DS} additional lost time due to demand starvation (s)

L_{ds} length of the stop line detection zone (ft)

$L_{ds,lt}$ length of the stop line detection zone in the left-turn lanes (ft)

$L_{ds,rt}$ length of the stop line detection zone in the right-turn lanes (ft)

$L_{ds,th}$ length of the stop line detection zone in the through lanes (ft)

$L_{D\text{-}Ui}$ lost time on the upstream approach i due to the presence of a downstream queue (s)

L_{EQ} equilibrium separation distance (ft)

L_h average vehicle spacing in stationary queue (ft/veh)

L_h^* effective average vehicle spacing in stationary queue (ft/veh)

$L_{h,k}^*$ effective average vehicle spacing in stationary queue during subperiod k (ft/veh)

L_{HV} stored heavy vehicle lane length (ft)

L_i length of segment or directional segment i (mi)

Location segment in which the incident occurs

$L_{OL\text{-}DDI}$ lost time on signalized external ramp approach at a DDI due to overlap phasing (s)

L_{pc} stored passenger car lane length (ft)

L_{pl} length of the passing lane (mi)

L_{pt} average passenger trip length (mi)

L_s distance between adjacent signalized intersections (ft, Chapter 18); weaving segment length (ft, Chapter 25)

L_S short length of the weaving segment, defined as the distance over which lane changing is not prohibited or dissuaded by markings (Chapter 13, ft); start-up lost time (s, Chapter 26)

$L_{seg(i)}$ length of segment i (ft)

l_t phase lost time (s)

L_t total length of the analysis segment (mi)

LTC left-turn flow rate per cycle (veh/cycle)

$LTDR$ left-turn demand ratio (decimal)

L_u length upstream of the passing lane (mi)

L_{UP} distance between the subject ramp junction and the adjacent upstream ramp junction (ft)

L_v detected length of the vehicle (ft)

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

LW lane width (ft)

L_{WI} influence area of the weaving segment (ft)

L_{wMAX} maximum length of a weaving segment (ft)

m number of segments on the facility (Chapter 16); move-up time (s, Chapter 21); number of lane groups served during the phase (Chapter 31)

M pedestrian space (ft²/p)

M_1 meetings per minute of users already on path segment

$M_{2,i}$ expected meetings per minute of users of mode i located beyond the end of the path segment at the time the average bicycle enters the segment

MAH maximum allowable headway (s/veh)

MAH^* equivalent maximum allowable headway for the phase (s/veh)

MAH_c maximum allowable headway for the concurrent phase that also ends at the barrier (s/veh)

$MAH_{lt,e}$ maximum allowable headway for permitted left-turning vehicles in exclusive lane (s/veh)

$MAH_{lt,e,p}$ maximum allowable headway for protected left-turning vehicles in exclusive lane (s/veh)

$MAH_{lt,s}$ maximum allowable headway for permitted left-turning vehicles in shared lane (s/veh)

$MAH_{lt,s,p}$ maximum allowable headway for protected left-turning vehicles in shared lane (s/veh)

$MAH_{rt,e,p}$ maximum allowable headway for protected right-turning vehicles in exclusive lane (s/veh)

$MAH_{rt,s}$ maximum allowable headway for permitted right-turning vehicles in shared lane (s/veh)

MAH_{th} maximum allowable headway for through vehicles (s/veh)

MaxProportion maximum proportion of work zone capacity available for mainline flow at the weave area (decimal)

M_{corner} corner circulation area per pedestrian (ft²/p)

M_{cw} crosswalk circulation area per pedestrian (ft²/p)

m_d set of all automobile movements that cross Crosswalk D

$MF(i, t, p)$ actual mainline flow rate that can cross node i during time step t in time interval p

MFlanes(s) number of mixed-flow lanes in section s (integer)

m_i average speed of mode i (mi/h)

$MI(i, t, p)$ maximum mainline input: maximum flow desiring to enter node i during time step t in time interval p

MinRate minimum ramp-metering rate (veh/h/ln)

MaxRate maximum ramp-metering rate (veh/h/ln)

m_j number of lane groups on approach j

$MO1(i, t, p)$ maximum Mainline Output 1: maximum allowable mainline flow rate across node i during time step t in time interval p, limited by the flow from an on-ramp at node i

$MO2(i, t, p)$ maximum Mainline Output 2: maximum allowable mainline flow rate across node i during time step t in time interval p, limited by available storage on segment i due to a downstream queue

$MO3(i, t, p)$ maximum Mainline Output 3: maximum allowable mainline flow rate across node i during time step t in time interval p, limited by the presence of queued vehicles at the upstream end of segment i while the queue clears from the downstream end of segment i

M_S speed index for on-ramps (merge areas)

MSF_i maximum service flow rate for LOS i (pc/h/ln)

M_T total number of expected meetings per minute during the peak 15 min

M_y motorist yield rate (decimal)

n number of segments in the defined facility (Chapter 10); average number of crossing events before an adequate gap is available (Chapter 20); number of lanes in the lane group (Chapter 23); number of extensions before the green interval reaches its maximum limit (Chapter 31)

N number of lanes in one direction (Chapter 11); number of lanes in analysis direction (Chapter 12); number of lanes required for a target LOS (Chapter 12); number of replications (Chapter 17); number of lanes in lane group (Chapter 19)

n_{15} count of vehicles during the peak 15-min period (veh)

$n_{15,mj}$ count of vehicles traveling on the major street during a 15-min period (veh/ln)

n_{60} count of vehicles during a 1-h period (veh)

N_A number of arterial lanes feeding the subject queue

N_{ap} number of analysis periods in 1 day (i.e., study period) (Chapter 17); number of influential access point approaches along the segment (Chapter 18, points)

$N_{ap,o}$ number of access point approaches on the right side in the opposing direction of travel (points)

$N_{ap,s}$ number of access point approaches on the right side in the subject direction of travel (points)

N_{Arterial} number of lanes for the upstream arterial through movement

N_b bus stopping rate on the subject approach (buses/h)

N_c total number of pedestrians in the crossing platoon (p, Chapter 20); number of circulating lanes (Chapter 30)

N_{comb} number of lanes for the combined movement (ln)

n_{cp} number of critical phases

N_d number of days in the reliability reporting period (Chapter 17); number of traffic lanes crossed in traversing Crosswalk D (ln, Chapter 19)

$n_{\text{Day},k}$ number of days in the reliability reporting period associated with demand combination k

N_{DC} number of demand combinations

$\bar{N}_{\text{DC,WZ}}$ adjusted number of replications of a demand combination for which the work zone is active

N_{di} number of pedestrians arriving at the corner each cycle having crossed the major street (p)

Nd_m number of days in month m (d)

N_{do} number of pedestrians arriving at the corner each cycle to cross the major street (p)

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

N_e number of exclusive lanes in movement group (ln)

N_f number of fully stopped vehicles (veh/ln)

$N_{f,sl}$ number of fully stopped vehicles in shared left-turn and through-lane group (veh/ln)

$N_{f,sr}$ number of fully stopped vehicles in shared right-turn and through-lane group (veh/ln)

$N_{f,t}$ number of fully stopped vehicles in exclusive through-lane group (veh/ln)

n_g arrival count during green (veh)

N_g number of lane groups for which t exceeds 0.0 h

N_{GP} number of general purpose lanes (ln)

$N_{GP,vert}$ average number of vehicles originating from the general purpose lanes that are waiting in the vertical queue in one analysis period (veh)

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

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

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

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

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

n_i number of lanes serving phase movement i

N_i number of lanes in segment i (Chapter 10); number of lanes associated with lane group i, with de facto lanes taken into account (ln, Chapter 31)

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

n_{inc} number of incidents

$N_{inc,i}$ number of incidents associated with severity type i

n_j expected frequency of all incidents in the study period for month j, rounded to the nearest integer

n_L number of vehicles that can be stored in the left-turn pocket

N_l number of lanes in exclusive left-turn lane group (ln)

N_L number of through lanes crossed

N_{lr} number of lanes in shared left- and right-turn lane group (ln)

N_{lt} number of lanes in the left-turn bay (ln)

n_m number of vehicles that can be stored in the median

N_m parking maneuver rate adjacent to lane group (maneuvers/h)

n_{Max} length of the storage area such that the approach would operate as separate lanes (veh)

$N_{ML,vert}$ average number of vehicles originating from the managed lanes that are waiting in the vertical queue in one analysis period (veh)

$N_{n,int(i),n,m}$ number of lanes serving movement m under normal (i.e., nonincident) conditions on leg associated with NEMA phase n at intersection i (ln)

n_o number of left-turn and through lanes open during normal operation (ln)

N_o number of open lanes in the work zone (ln)

N_O number of outer lanes on the freeway (1 for a six-lane freeway; 2 for an eight-lane freeway)

N_p spatial distribution of pedestrians (p, Chapter 20); number of partial stops (Chapter 31)

n_{ped} number of conflicting pedestrians (p/h)

N_{ped} number of pedestrians crossing during an interval (p)

$N_{ped,do}$ number of pedestrians waiting at the corner to cross the major street (p)

n_q maximum number of opposing vehicles that could arrive after g_f and before g_u (veh)

N_{qa} available queue storage (veh)

N_{qx} maximum queue storage for the movement (veh)

$N_{qx,lt}$ maximum queue storage for the left-turn movement (veh)

$N_{qx,lt,n,k}$ maximum queue storage for left-turn movement group during subperiod k (veh)

$N_{qx,thru}$ maximum queue storage for the through movement (veh)

$N_{qx,thru,n,k}$ maximum queue storage for through movement group during subperiod k (veh)

$N_{qx,turn}$ maximum queue storage for a turn movement (veh)

n_R actual storage area for right-turning vehicles

N_r number of replications of a demand combination (Chapter 25); number of lanes in exclusive right-turn lane group (Chapter 31, ln)

N_R number of ramp lanes feeding the subject queue (ln)

NR number of metered lanes on ramp (ln)

$N_{Ramp\text{-}L}$ number of lanes for the upstream ramp left-turning movement (ln)

$N_{rtci,d}$ number of right-turn channelizing islands along Crosswalk D

n_s number of sneakers per cycle

n_s^* expected number of sneakers per cycle in a shared left-turn lane

N_s number of segments forming the facility (Chapter 15); number of signals within study section of facility (unitless, Chapter 17)

NS number of segments on the facility

N_{scen} number of scenarios in the analysis

$N_{scen,Inc}$ number of all incident events generated for all scenarios

$N_{scen,j}$ number of scenarios associated with month j of the reliability reporting period

N_{sl} number of lanes in shared left-turn and through lane group (ln)

N_{sr} number of lanes in shared right-turn and through lane group (ln)

N_t number of lanes in exclusive-through lane group (ln, Chapters 18, 30, and 31); total number of stops (Chapter 31)

$N_{t,i,j}$ number of lanes in exclusive-through lane group j at intersection i (ln)

N_{th} number of through lanes (shared or exclusive) (ln)

N_{tot} total number of circulating pedestrians arriving each cycle (p)

N_{ts} number of transit stops on the segment for the subject route (stops)

N_{turn} number of lanes in the turn bay (ln)

N_{tw} number of turning vehicles during the walk and pedestrian clear intervals (veh)

N_{unblk} number of open lanes when blockage is present (ln)

$NV(i, t, p)$ number of vehicles present on segment i at the end of time step t during time interval p

N_{WL} number of lanes from which a weaving maneuver may be completed with one lane change or no lane changes (ln)

n_{wz} number of left-turn and through lanes open during work zone presence (ln)

n_x number of calls necessary to extend the green to max out

Ny total number of years (years)

$O_{a,i}$ adjusted volume for origin *i* (veh/h)

OCC_{bicg} average bicycle occupancy

OCC_{pedg} pedestrian occupancy

OCC_{pedu} pedestrian occupancy after the opposing queue clears

OCC_r relevant conflict-zone occupancy

$OFRD(i, p)$ desired off-ramp demand flow exiting at off-ramp *i* during time interval *p*

$OFRF(i, t, p)$ actual flow that can exit at off-ramp *i* during time step *t* in time interval *p*

O_i volume for origin *i* (veh/h)

O_{MAIN} offset at the downstream main intersection (s)

$ONRC(i, p)$ geometric carrying capacity of on-ramp at node *i* roadway during time interval *p*

$ONRD(i, p)$ demand flow rate for on-ramp at node *i* in time interval *p*

$ONRF(i, t, p)$ actual ramp flow rate that can cross on-ramp node *i* during time step *t* in time interval *p*

$ONRI(i, t, p)$ input flow rate desiring to enter the merge point at on-ramp *i* during time step *t* in time interval *p*

$ONRO(i, t, p)$ maximum output flow rate that can enter the merge point from on-ramp *i* during time step *t* in time interval *p*

$ONRQ(i, t, p)$ unmet demand that is stored as a queue on the on-ramp roadway at node *i* during time step *t* in time interval *p* (veh)

OR open ratio, the ratio of the number of open lanes during road work to the total (or normal) number of lanes (decimal)

O_{SUPP} offset at the upstream supplemental intersection (s)

p probability of a call headway being less than the maximum allowable headway

P Federal Highway Administration 5-point pavement surface condition rating (Chapter 15); proportion of vehicles arriving during the green indication (Chapters 18, 19, and 23); number of (15-min) analysis periods in the study period (Chapter 25)

$P(a_j)$ probability of a_j

$P(C_i)$ probability of degree-of-conflict case *i*

$P(i)$ probability of each combination *i*

$P(precip)_m$ probability of precipitation in any given day of month *m*

$P(v_i)$ probability of passing user of mode *i*

$P(v_{O,i})$ probability of meeting opposing user of mode *i*

$P(Y_i)$ probability that motorists yield to pedestrian on crossing event *i*

$P\{s\}$ probability of scenario *s*

p' adjustment to the major-street left, minor-street through impedance factor

$p'_{b,x}$ proportion of time blocked for isolated DDI analysis (decimal)

$P'(i)$ adjusted probability of each combination *i*

p'' intermediate calculation variable

$p_{0,j}$ probability of a queue-free state for the conflicting major-street left-turning traffic

$p^*_{0,j}$ probability that there will be no queue in the inside through lane (Chapters 16 and 18); proportion of Rank 1 vehicles not blocked (Chapter 20)

$p_{0,k}$ probability of a queue-free state for the conflicting minor-street crossing traffic

$p0_{str(i)}$ probability of no incident for street location *i* of type *str*

P_a proportion of automobiles in the traffic stream

$p_{ap,lt}$ proportion of $N_{ap,o}$ that can be accessed by a left turn from the subject direction of travel

p_b probability of a blocked lane (Chapter 20); proportion of time blocked (decimal, Chapter 30)

$p_{b,x}$ proportion of time that movement x is blocked by a platoon

P_{BCDEF} probability that an individual will respond with a score of B, C, D, E, or F

p_{be} proportion of stops on segment with benches (decimal)

P_{bo} probability of two blocked lanes in the opposing direction

P_{bs} probability of two blocked lanes in the subject direction

p_{building} proportion of sidewalk length adjacent to a building face (decimal)

p_c probability that the subject phase is called

P_c pavement condition rating

PC pedestrian clear setting (s)

P_{CDEF} probability that an individual will respond with a score of C, D, E, or F

PC_{mi} pedestrian clear setting for the phase serving the minor-street through movement (s)

p_{curb} proportion of segment with curb on the right-hand side (decimal)

P_d probability of a delayed crossing

P_{DEF} probability that an individual will respond with a score of D, E, or F

P_{do} probability of delayed passing in opposing direction

P_{ds} probability of delayed passing in subject direction

P_{EF} probability that an individual will respond with a score of E or F

P_F probability that an individual will respond with a score of F

PF progression adjustment factor

PF^* simplified progression adjustment factor

P_{FD} proportion of diverging traffic remaining in Lanes 1 and 2 immediately upstream of the deceleration lane

p_{fence} proportion of sidewalk length adjacent to a fence or low wall (decimal)

$PFFS$ percentage of free-flow speed (decimal)

P_{FM} proportion of through freeway traffic remaining in Lanes 1 and 2 immediately upstream of the deceleration lane (decimal)

P_g approach grade (%)

$p_{GA,x}$ proportion of time of gap acceptance regime (decimal)

PHF peak hour factor (decimal)

P_{HV} percentage of heavy vehicles (%, Chapters 18 and 19); proportion of heavy vehicles (decimal, Chapters 20 and 21)

P_{HVa} adjusted percentage of heavy vehicles in the midsegment demand flow rate (%)

p_i path mode split for user group i (Chapter 24); distance required to pass mode i (mi, Chapter 24)

$p_{i,j}$ seed proportion of volume from origin i to destination j (decimal)

pi_{str} proportion of incidents for street location type *str*

P_L proportion of left-turning vehicles in the shared lane

P_{lc} probability of a lane change among the approach through lanes

$P_{LL,t}$ proportion of through-movement vehicles in the left lane (decimal)

P_{lt} proportion of left-turning vehicles on the subject approach (decimal)

P_{LT} proportion of left-turning vehicles in the lane

$P_{LTL,seg}$ proportion of intersections with left-turn lanes (or bay) on segment (decimal)

P_{lto} proportion of left-turning vehicles in the opposing traffic stream

P_{mds} probability of delayed passing for mode m

$P_{n,i}$ probability of passing section being blocked by mode i

$p_{NCF,x}$ proportion of time of no conflicting flow (decimal)

P_{no} probability of blocked lane in opposing direction

P_{ns} probability of blocked lane in subject direction

p_{ot} proportion of transit vehicles arriving on time (decimal)

p_{ov} probability of left-turn bay overflow (decimal)

p_p probability that the subject phase is called by a pedestrian detection

P_p probability of a pedestrian pressing the detector button

$p_{p,j}$ probability that conflicting Rank 2 pedestrian movement j will operate in a queue-free state

$p_{p,x}$ pedestrian impedance factor for pedestrian movement x

p_{pk} proportion of on-street parking occupied (decimal)

P_R proportion of recreational vehicles in the traffic stream (Chapter 15); proportion of right-turning vehicles in the shared lane (Chapter 18)

$P_{R,i,j,k}$ proportion of right-turning vehicles in the shared lane group j at intersection i for subperiod k

$P_{RL,t}$ proportion of through-movement vehicles in the right lane (decimal)

p_{rm} proportion of link length with restrictive median (decimal)

Prop(off-ramp) off-ramp demand volume proportion

Proportion proportion of work zone capacity available for mainline flow (decimal)

P_{rt} proportion of right-turning vehicles on the subject approach (decimal)

P_{RT} proportion of right-turning vehicles in the lane or lane group

p_{sh} proportion of stops on segment with shelters (decimal)

P_{SUT} proportion of single-unit trucks in the traffic stream (decimal)

$P_t[w, j]$ timewise probability of weather type w in month j

P_T proportion of trucks or heavy vehicles in the traffic stream

PT passage time setting (s)

PT_{45} percentage of trips that occur at speeds less than 45 mi/h (decimal)

P_{TC} proportion of trucks operating at crawl speed (decimal)

P_{Tds} total probability of delayed passing

PTI planning time index

PT_{lt} passage time setting for phase serving left-turning vehicles (s)

PT_{rt} passage time setting for phase serving right-turning vehicles (s)

$PTSF_d$ percent time-spent-following in the analysis direction (decimal)

$PTSF_F$ percent time-spent-following for the facility (decimal)

$PTSF_i$ percent time-spent-following for segment i (decimal)

$PTSF_{pl}$ percent time-spent-following for segment as affected by the presence of a passing lane (decimal)

P_{TT} proportion of tractor trailers in the traffic stream (decimal)

PT_{th} passage time setting for phase serving through vehicles (s)

P_{turn} proportion of turning vehicles in the shared lane (decimal)

p_v probability that the subject phase is called by a vehicle detection

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

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

$P_W(i, j)$ probability of encountering weather type i in month j

P_{window} proportion of sidewalk length adjacent to a window display (decimal)

p_x probability of phase termination by extension to the maximum green limit

q arrival flow rate (veh/s)

Q back-of-queue size (veh/ln)

$Q(i, t, p)$ total queue length on segment i at the end of time step t in time interval p (ft)

q^* arrival flow rate for the phase (veh/s)

q_p^* activating pedestrian call rate for the phase (p/s)

q_v^* activating vehicular call rate for the phase (veh/s)

$q'_{a|u,j}$ arrival flow rate in time step j at a downstream intersection from upstream source u (veh/step)

$q'_{u,i}$ departure flow rate in time step i at upstream source u (veh/step)

$Q_{\%}$ percentile back-of-queue size (veh/ln)

Q_1 first-term back-of-queue size (veh/ln)

Q_2 second-term back-of-queue size (veh/ln)
$Q_{2,d}$ average queue size associated with the deterministic delay component
$Q_{2,sl}$ second-term back-of-queue size for shared left-turn and through lane group (veh/ln)
$Q_{2,sr}$ second-term back-of-queue size for shared right-turn and through lane group (veh/ln)
$Q_{2,t}$ second-term back-of-queue size for exclusive-through lane group (veh/ln)
Q_{2+3} back-of-queue size (veh/ln)
Q_3 third-term back-of-queue size (veh/ln)
$Q_{3,sl}$ third-term back-of-queue size for shared left-turn and through lane group (veh/ln)
$Q_{3,sr}$ third-term back-of-queue size for shared right-turn and through lane group (veh/ln)
$Q_{3,t}$ third-term back-of-queue size for exclusive-through lane group (veh/ln)
Q_{95} 95th percentile queue (veh)
Q_A estimated average per lane queue length for the through movement in the downstream (internal) link at the beginning of upstream arterial Phase A (ft)
Q_b initial queue at the start of the analysis period (veh)
$Q_{b,comb}$ initial queue for the combined movement (veh)
$Q_{b,thru}$ initial queue for the through movement (veh)
q_c conflicting flow rate (veh/h)
q_d arrival flow rate for downstream lane group (veh/s)
QDR_{wz} average 15-min queue discharge rate (pc/h/ln) at the work zone bottleneck
Q_e queue at the end of the analysis period (veh)
Q_{eo} queue at the end of the analysis period when $v \geq c_A$ and $Q_b = 0.0$ (veh)
Q_f queue size at the end of g_f (veh)
q_g arrival flow rate during the effective green time (veh/s)
q_i hourly directional path flow rate for user group i (modal users/h)
Q_i queue size at the end of interval i (veh)
$q_{i,t}$ demand flow rate on section i during analysis period t (pc/h)
$Q_{i,max}$ maximum queue length for direction i (pc)
Q_{Initial} length of the queue stored at the internal approach at the beginning of the interval during which this approach has demand starvation potential
q_n outside lane flow rate (veh/s)
Q_{ob} bicycle demand in the opposing direction (bicycles/h)
Q_p queue size at the end of permitted service time (veh)
Q'_p queue size at the end of permitted service time, adjusted for sneakers (veh)
Q_q queue size at the start of g_u (veh)
q_r arrival flow rate during the effective red time (veh/s)
Q_r queue size at the end of effective red time (veh)
Q_R estimated average per lane queue length for the through movement in the downstream (internal) link at the beginning of upstream ramp Phase R (ft)
$QR(t-1)$ queue on ramp at end of previous analysis period $t-1$ (veh)
QRS queue storage capacity of ramp (veh)
Q_{sb} bicycle demand in the same direction (bicycles/h)
Q_{sep} average queue length for the movement considered as a separate lane (veh)
Q_T total hourly directional path demand (modal users/h)
Q_{tdo} total time spent by pedestrians waiting to cross the major street during one cycle (p-s)
r effective red time (s)
R red time (s, Chapter 19); radius of corner curb (ft, Chapter 19); intermediate calculation variable (Chapter 30); critical flow ratio for the exit-ramp movements (Chapter 34)
$R(t)$ ramp-metering rate for analysis period t (veh/h/ln)
R_1 critical flow ratio for the exit-ramp movements for Intersection I

$R_{I,II}$ critical flow ratio for the exit-ramp movements for the interchange
R_{II} critical flow ratio for the exit-ramp movements for Intersection II
r_a acceleration rate (ft/s²)
r_{at} transit vehicle acceleration rate (ft/s²)
R_c red clearance interval (s)
$R_{c,mi}$ red clearance interval of the phase serving the minor-street through movement (s)
$r_{c,th}$ average radius of the circulating path of the through movement (ft)
r_d deceleration rate (ft/s²)
r_{DC} ratio of weekday types with an active work zone in a given month to the total number of each weekday type occurring in a given month
RDR recurring delay rate (h/mi)
$Rd_{str(i)}$ random number for incident duration for street location *i* of type *str*
r_{dt} transit vehicle deceleration rate (ft/s²)
$Rf_{ap,d}$ random number for flow rate for analysis period *ap* and day *d*
Rg_d random number for temperature for day *d*
RIA_1 roundabout influence area for Subsegment 1 (ft)
$Ri_{str(i)}$ random number for incident for street location *i* of type *str*
$RM(i, p)$ maximum allowable rate of an on-ramp meter at the on-ramp at node *i* during time interval *p* (veh/h)
R_p platoon ratio
$Rp_{d,m}$ random number for precipitation for day *d* of month *m*
R_Q queue storage ratio
$R_{Q\%}$ percentile queue storage ratio
r_{qg} queue growth rate (veh/h)
$R_{r,ap,d}$ rainfall rate during analysis period *ap* and day *d* (in./h)
Rr_d random number for rainfall rate for day *d*
$rr_{d,m}$ rainfall rate for the rain event occurring on day *d* of month *m* (in./h)
$\overline{rr}_m$ precipitation rate in month *m* (in./h)
$R_{s,ap,d}$ precipitation rate when snow is falling during analysis period *ap* and day *d* (in./h)
$R_{s,d}$ random number for rain event start time for day *d*
Rt_d random number for rainfall total for day *d*
$Rv_{int(i)}$ random number for leg volume for intersection *i*
$Rv_{seg(i)}$ random number for volume for segment *i*
RW reciprocal of path width (ft)
s saturation flow rate (veh/h, Chapter 4); mean service rate (veh/h, Chapter 4); standard deviation of the subject performance measure (Chapter 17); adjusted saturation flow rate (veh/h/ln, Chapter 18)
S peak hour speed (mi/h, Chapter 11); mean speed of traffic stream under base conditions (mi/h, Chapter 12); number of computational time steps in an analysis period (integer, Chapter 25)
$S(t, d)$ arithmetic average speed of vehicles (mi/h) measured during time period *t* at lane detector station *d*
s_0 base saturation flow rate (pc/h/ln)
S_0 speed constant (mi/h)
S_{0i} free-flow speed of segment *i* (mi/h)
s_1 saturation flow rate for the inside lane (veh/h/ln)
S_1 speed within the linear portion of the speed–flow curve (mi/h)
$S_{1,BP}$ speed at the breakpoint of the speed–flow curve
S_2 speed drop within the curvilinear portion of the speed–flow curve (mi/h)
S_3 additional speed drop (mi/h) within the curvilinear portion of the speed–flow curve when the density of the adjacent general purpose lane is more than 35 pc/mi/ln
$S_{85,mj}$ 85th percentile speed at a midsegment location on the major street (mi/h)

S_a average speed (mi/h, Chapter 30); average speed on the intersection approach (mi/h, Chapter 31)
SAF speed adjustment factor (decimal)
SAF_{cal} free-flow speed adjustment factor for calibration purposes
SAF_{mix} mixed-flow speed adjustment factor for the basic freeway segment (decimal)
SAF_{wz} free-flow speed adjustment factor for a work zone (decimal)
S_{ao} automobile-only speed for the given flow rate (mi/h)
s_b saturation flow rate of the bicycle lane (bicycles/h)
S_b bicycle running speed (mi/h, Chapter 18); mean bicycle speed on path (mi/h, Chapter 24)
S_c circulating speed (mi/h)
$SC(i, p)$ segment capacity: maximum number of vehicles (veh/h) that can pass through segment i in time interval p based strictly on traffic and geometric properties
S_{calib} base free-flow speed calibration factor (mi/h)
$S_{calib,90cap}$ mixed-flow speed at 90 percent of capacity (mi/h)
$S_{calib,cap}$ mixed-flow speed at capacity (mi/h)
$SD(i, p)$ segment demand: desired flow rate (veh/h) through segment i including on- and off-ramp demands in time interval p
s_{DDI} saturation flow rate for the DDI approach (veh/h)
S_f free-flow speed (mi/h)
SF service flow rate (veh/h)
$SF(i, t, p)$ segment flow (veh/h) out of segment i during time step t in time interval p
$S_{f,1,initial}$ initial free-flow speed for Subsegment 1 (mi/h)
$S_{f,DDI}$ free-flow speed between the DDI crossover stop bar and the yield conflict point (mi/h)
SF_i service flow rate for LOS i (veh/h)
SFI_i service flow rate under ideal conditions (pc/h)
S_{FM} mean speed of sample (v > 200 veh/h) (mi/h)
$S_{f,non\text{-}rbt}$ free-flow speed for nonroundabout segments (mi/h)
S_{fo} base free-flow speed (mi/h)
$S_{fo,F}$ base free-flow speed for the facility (mi/h)
$S_{fo,i}$ base free-flow speed for segment i (mi/h)
$S_{fo,seg,i,ap,d}$ base free-flow speed of through vehicles for segment i during analysis period ap and day d (mi/h)
$S^*_{fo,seg(i),n,ap,d}$ adjusted base free-flow speed for the direction of travel served by NEMA phase n on segment i during analysis period ap and day d (ft/s)
S_{FR} free-flow speed of the ramp (mi/h)
s_i saturation flow rate for lane group or phase movement i (veh/h/ln)
S_i average vehicle speed on segment i or in direction i (mi/h)
$S_{i,fps}$ average travel speed in direction i (ft/s)
$S_{i,t}$ average speed on section i in analysis period t (mi/h)
s_{t1} saturation flow rate for the major-street through movements (veh/h)
s_{t2} saturation flow rate for the major-street right-turn movements (veh/h)
s_l saturation flow rate in exclusive left-turn lane group with permitted operation (veh/h/ln)
s_{l1} saturation flow rate in the exclusive left-turn lane group during Period 1 (veh/h/ln)
s_{lc} maximum flow rate in which a lane change can occur (veh/h/ln)
s_{lr} saturation flow rate in shared left- and right-turn lane group (veh/h/ln)
s_{lt} saturation flow of an exclusive left-turn lane with protected operation (veh/h/ln)
SL_{wz} work zone speed limit (mi/h)
S_m speed for mode m (mi/h)
S_{MAX} maximum average speed of weaving vehicles expected in a weaving segment (mi/h)
S_{MIN} minimum average speed of weaving vehicles expected in a weaving segment (mi/h)

$S_{mix,j}$ space-based speed (mi/h)
$S_{mix,oa}$ overall mixed-flow speed (mi/h)
S_{ML} space mean speed of the basic managed lane segment (mi/h)
$SMS(NS, p)$ average time interval facility speed: average space mean speed over the entire facility during time interval p
$SMS(NS, P)$ average analysis period facility speed: average space mean speed over the entire facility during the entire analysis period P
$SMS_p(NS)$ facility space mean speed in time interval p
S_{NW} average speed of nonweaving vehicles within the weaving segment (mi/h)
s_o base saturation flow rate (pc/h/ln)
S_O average speed of vehicles in outer lanes of the freeway, adjacent to the 1,500-ft ramp influence area (mi/h)
$s_{o,local}$ local base saturation flow rate (pc/h/ln)
s_p saturation flow rate of a permitted left-turn movement (veh/h/ln)
S_p posted speed limit (mi/h, Chapter 15); pedestrian walking speed (ft/s, Chapters 18, 20, 24, and 31)
S_{ped} pedestrian speed (ft/min)
S_{pf} free-flow pedestrian walking speed (ft/s)
S_{pl} posted speed limit (mi/h)
$s_{prevailing,i}$ prevailing saturation flow rate for lane group i (veh/h/ln)
s_{q1r} shared lane discharge flow rate for upstream right-turn traffic movement (veh/h/ln)
s_r saturation flow rate in exclusive right-turn lane group with permitted operation (veh/h/ln)
S_R average speed in the ramp influence area (mi/h, Chapter 14); motorized vehicle running speed (mi/h, Chapter 18)
S_{Ra} adjusted motorized vehicle running speed (mi/h)
$s_{rr,m}$ standard deviation of precipitation rate in month m (in./h)
s_{rt} saturation flow rate of an exclusive right-turn lane with protected operation (veh/h/ln)
S_{Rt} transit vehicle running speed (mi/h)
S_s threshold speed defining a stopped vehicle (mi/h)
s_{sl} saturation flow rate in shared left-turn and through lane group with permitted operation (veh/h/ln)
s_{sl2} saturation flow rate in shared left-turn and through lane group during Period 2 (veh/h/ln)
S_{spot} average spot speed (mi/h)
s_{sr} saturation flow rate in shared right-turn and through lane group with permitted operation (veh/h/ln)
s_{str} standard deviation of incident duration for street location type str
s_t saturation flow rate in exclusive-through lane group (veh/h/ln)
s_T standard deviation of daily mean temperature in a month (°F)
S_t effective speed factor
$S_{T,F}$ travel speed for the facility (mi/h)
$S_{T,seg}$ travel speed of through vehicles for the segment (mi/h)
$S_{T,seg,i,ap,d}$ travel speed of through vehicles for segment i during analysis period ap and day d (mi/h)
$StartTime$ analysis period in which the incident starts
$S_{Tb,F}$ travel speed of through bicycles for the facility (mi/h)
$S_{Tb,seg}$ travel speed of through bicycles along the segment (mi/h)
ST_{DLT} system start time of the displaced left-turn phase (s)
s_{th} saturation flow rate of an exclusive through lane (veh/h/ln)
$S_{Tp,F}$ travel speed of through pedestrians for the facility (ft/s)
$S_{Tp,seg}$ travel speed of through pedestrians for the segment (ft/s)
$S_{Tt,F}$ travel speed of transit vehicles for the facility (mi/h)

$S_{Tt,seg}$ travel speed of transit vehicles along the segment (mi/h)

ST_{TH} system start time of the major-street through phase (s)

SV_i service volume for LOS i (veh/h)

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

s_{w-r} transit wait–ride score

t duration of unmet demand in the analysis period (h, Chapter 19); path segment travel time for average bicycle (min, Chapter 24)

T analysis time period (h, Chapters 19 and 20); number of time steps in 1 h (integer, Chapter 25)

t' platoon arrival time (steps)

t'_p blocked period duration (steps)

t'_R segment running time (steps)

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

T_0 time at which a vehicle would have arrived at the stop line if it had been traveling at the reference speed (s)

T_1 time at which a vehicle would have arrived at the stop line if it had been traveling at the running speed (s)

T_2 time at which a vehicle is discharged at the stop line (s)

$t_{3,LT}$ adjustment factor for intersection geometry

T_{10000} kinematic travel rate at 10,000 ft (s/mi)

t_a average duration of unmet demand in the analysis period (h)

t_A adjusted duration of unmet demand in the analysis period (h)

T_{at} amenity time rate (min/mi)

T_{btt} base travel time rate (min/mi)

T_c time until spillback (h)

t_c queue clearing time (h, Chapter 19); critical headway for a single pedestrian (s, Chapter 20)

$t_{c,base}$ base critical headway (s)

$t_{c,G}$ adjustment factor for grade (s, Chapter 20); group critical headway (s, Chapter 20)

$t_{c,HV}$ adjustment factor for heavy vehicles (s)

$t_{c,x}$ critical headway for movement x (s)

t_{cg} critical headway (s)

t_{cl} clearance time of the right-turn vehicle (s)

t_{clear} time for last queued vehicle to clear distance from stop bar to yield point (s)

t_{CQ} time to clear conflicting queue (s)

$t_{CQ,coord}$ time to clear conflicting queue for a coordinated interchange (s)

$t_{CQ,free}$ time to clear conflicting queue for an isolated interchange with random arrivals (s)

$T_{cs,k}$ controlling time until spillback for the subperiod k (h)

t_d dwell time (s)

$t_{d,i}$ duration of time interval i during which the arrival flow rate and saturation flow rate are constant (s)

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

TD_{DLT} travel distance from upstream stop line to downstream stop line for the displaced left-turn roadway (ft)

t_{ex} excess wait time due to late arrivals (s)

T_{ex} excess wait time rate due to late arrivals (min/mi)

t_f follow-up headway (s, Chapter 22); service time for fully stopped vehicles (s, Chapter 31)

$t_{f,base}$ base follow-up headway (s)

$t_{f,HV}$ adjustment factor for heavy vehicles (s)

$t_{f,x}$ follow-up headway for movement x (s)

t_{fh} follow-up headway (s)

t_i lost time for *i*th vehicle in queue (s, Chapter 4); duration of unmet demand for lane group *i* in the analysis period (h, Chapter 19)
$T_{i,t}$ travel time on segment *i* in analysis period *t* (min/mi)
t_l transit vehicle running time loss (min/mi)
t_L lost time per phase (s)
t'_L adjusted lost time (s)
t''_L adjusted lost time for the internal approaches (s)
t_{late} threshold late time (min)
t_{lc} critical merge headway (s)
TLC total lateral clearance (ft)
$\overline{T}_m$ normal daily mean temperature in month *m* (°F)
T_{max} wave travel time (s)
$t_{mix,j}$ mixed-flow travel time for segment *j* (s)
$t_{mix,oa}$ overall mixed-flow travel time (s)
T_o analysis period duration for the first subperiod (h)
T_{occ} crosswalk occupancy time (p-s)
T_p analysis time period
tp_m total normal precipitation for month *m* (in.)
t_{pr} driver starting response time (s/veh, Chapter 30); pedestrian perception of signal indication and curb departure time (s, Chapter 31)
t_{ps} pedestrian service time (s)
$t_{ps,do}$ service time for pedestrians who arrive at the corner to cross the major street (s)
T_{ptt} perceived travel time rate (min/mi)
t_Q duration of queue (s)
t_R segment running time (s)
$t_{R,agg,m,all}$ aggregated segment running time for site *m* for all *n* subperiods (s)
$t_{R,m}$ segment running time for site *m* (s)
t_{Rb} segment running time of through bicycles (s)
TRD total ramp density (ramps/mi)
$tr_{d,m}$ total rainfall for the rain event occurring on day *d* of month *m* (in./event)
TR_{FFS} travel rate under free-flow conditions (min/mi)
$TR_{i,t}$ travel rate on segment *i* in analysis period *t* (min/mi)
$\overline{tr}_m$ average total rainfall per event in month *m* (in./event)
t_{Rt} segment transit vehicle running time (s)
t_s pedestrian start-up time and end clearance time (s, Chapter 20); service time (s, Chapter 21)
TS_c time-space available for circulating pedestrians (ft²-s)
TS_{corner} available corner time-space (ft²-s)
TS_{cw} available crosswalk time-space (ft²-s)
TS^*_{cw} effective available crosswalk time-space (ft²-s)
$ts_{d,m}$ start of rain event on day *d* of month *m* (h)
TS_{tv} time-space occupied by turning vehicles (ft²-s)
T_T travel time (s)
$t_{t,i}$ duration of trapezoid or triangle in interval *i* (s)
TT_{DLT} left-turn travel time (s)
$\overline{TT}_F$ average travel time for through trips on the facility during the reliability reporting period (s)
$\overline{TT}_{fo,F}$ average travel time for through trips at the base free-flow speed on the facility during the reliability reporting period (s)
TT_i total travel time of all vehicles in segment *i* (veh-h)
TTI travel time index (unitless)

TT_{i15} total travel time consumed by all vehicles traversing directional segment i during the 15-min analysis period (veh-h)

TTI_{50} 50th percentile travel time index (unitless)

TTI_{95} 95th percentile travel time index or planning time index (unitless)

TTI_{mean} average annual mean travel time index (unitless)

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

TTI_{pp} percentile travel time index (unitless)

TTI_t travel time index for the facility during time period t (unitless)

$\overline{TT}_p$ agency's maximum acceptable travel time for through trips on the facility during the reliability reporting period (s)

$T_{total,k}$ total analysis time for subperiods 0 to k (h)

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

U speed of average bicyclist (mi/h)

$U(i, p)$ average space mean speed over the length of segment i during time interval p (mi/h)

u_m minimum speed of the first through vehicle given that it is delayed (ft/s)

u_{rt} right-turn speed (ft/s)

$UV(i, t, p)$ unserved vehicles: the additional number of vehicles stored on segment i at the end of time step t in time interval p due to a downstream bottleneck

v mean arrival rate (veh/h, Chapter 4); base demand volume (veh/h, Chapter 10); demand flow rate (pc/h, Chapter 12); total demand flow rate in the weaving segment (pc/h, Chapter 13); conflicting vehicular flow rate (veh/s, Chapter 20)

V demand volume under prevailing conditions (veh/h, Chapter 12); movement volume (veh/h, Chapter 31)

$V(t, d)$ sum of lane volumes (veh) measured at detector station d during time period t

v_1 flow rate for the inside lane (veh/h/ln)

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

v_{12a} adjusted flow rate in Lanes 1 and 2 immediately upstream of the ramp influence area (pc/h)

v_{15} pedestrian flow rate during the peak 15 min (p/h)

V_{15} volume during the peak 15 min of the analysis hour (veh/15 min)

v_2 flow rate in the adjacent through lane (veh/h/ln)

v_3 flow rate in Lane 3 of the freeway (pc/h/ln)

v_5 estimated approaching freeway flow in Lane 5 (pc/h)

v_A arterial flow feeding subject queue (veh/h)

V_a average speed of moving queue (ft/s)

$v_{a,1}$ adjusted arrival volume in the shared lane (veh/h)

$v_{a,b}$ flow rate of pedestrians traveling through the corner from Sidewalk A to Sidewalk B, or vice versa (p/h)

$v_{a,thru}$ adjusted arrival volume for the subject through movement (veh/h)

$v_{a,turn}$ adjusted arrival volume for the subject turn movement (veh/h)

$v_{A,x}$ volume or flow rate on approach x (veh/h)

v_{adj} adjusted demand input volume (veh/h, Chapter 10); equivalent through movement flow rate expressed in through passenger cars per hour (tpc/h, Chapter 31)

$v_{adj,i}$ equivalent through movement flow rate for lane group i (tpc/h)

v_{app} approach flow rate (veh/h, Chapter 23); average demand flow rate per through lane (upstream of any turn bays on the approach) (veh/h/ln, Chapter 30)

$v_{app,g}$ arrival flow rate during green (veh/h)

$v_{app,r}$ arrival flow rate during red (veh/h)

$v_{Arterial}$ upstream arterial through flow (veh/h)

v_{av34} flow rate in outer lanes (pc/h/ln)

v_{bic} bicycle flow rate (bicycles/h)

v_{bicg} bicycle flow rate during the green indication (bicycles/h)

v_{bypass} volume in the bypass lane (veh/h)

v_c conflicting or circulating flow rate (veh/h)

V_c sum of the critical-lane flow rates (tpc/h/ln)

$v_{c,i}$ lane flow rate for critical lane group *i* (tpc/h/ln)

$v_{c,min}$ minimum platooned flow rate (veh/h)

$v_{c,pce}$ conflicting flow rate (pc/h)

$V_{c,perm,1}$ critical-lane flow rate for permitted left-turn operation on the east–west approaches (tpc/h/ln)

$V_{c,perm,2}$ critical-lane flow rate for permitted left-turn operation on the north–south approaches (tpc/h/ln)

$V_{c,prot,1}$ critical-lane flow rate for protected left-turn operation on the east–west approaches (tpc/h/ln)

$V_{c,prot,2}$ critical-lane flow rate for protected left-turn operation on the north–south approaches (tpc/h/ln)

$V_{c,split,1}$ critical-lane flow rate for split phasing on the east–west approaches (tpc/h/ln)

$V_{c,split,2}$ critical-lane flow rate for split phasing on the north–south approaches (tpc/h/ln)

$v_{c,u,x}$ conflicting flow for movement *x* during the unblocked period (veh/h)

$v_{c,x}$ conflicting flow rate for movement *x* (veh/h)

v_{ci} flow rate of pedestrians arriving at the corner after crossing the minor street (p/h)

v_{co} flow rate of pedestrians arriving at the corner to cross the minor street (p/h)

v_D flow rate on the adjacent downstream ramp (pc/h, Chapter 14); design speed of the loop ramp or diverted movement (mi/h, Chapter 23)

$v_{d,ATS}$ demand flow rate for ATS estimation (pc/h)

$v_{d,PTSF}$ demand flow rate in the analysis direction for estimation of PTSF (pc/h)

v_{di} flow rate of pedestrians arriving at the corner after crossing the major street (p/h)

v_{do} flow rate of pedestrians arriving at the corner to cross the major street (p/h)

$V_{dOFF15ij}$ adjusted 15-min exit demand for time period *i* and exiting location *j* (veh)

v_e entry flow rate

v_{ex} exiting flow rate

$v_{ex,pce}$ conflicting exiting flow rate (pc/h)

v_F flow rate on freeway immediately upstream of the ramp influence area under study (pc/h)

v_{F4eff} effective approaching freeway flow in four lanes (pc/h)

v_{FF} freeway-to-freeway demand flow rate in the weaving segment (pc/h)

v_{FO} flow rate on the freeway immediately downstream of the merge or diverge area (pc/h)

v_{FR} freeway-to-ramp demand flow rate in the weaving segment (pc/h)

v_g demand flow rate for movement group (veh/h)

v_{g1} demand flow rate in the single exclusive lane with the highest flow rate of all exclusive lanes in movement group (veh/h/ln)

v_h pedestrian demand during the analysis hour (p/h)

$VHT(t, d)$ vehicle hours traveled during time period *t* measured at lane detector station *d*

$VHTFF_t$ facility vehicle hours traveled during time period *t* if travel was at free-flow speed

VHT_t facility vehicle hours traveled during time period *t*

$VHT_{t,d}$ vehicle hours traveled during time period *t* measured at lane detector station *d*

v_i demand flow rate for movement *i* (pc/h, Chapters 13, 19, and 20); actual or projected demand flow rate for lane group *i* (veh/h, Chapter 23); speed of a given path user of mode *i* (mi/h, Chapter 24); flow rate for lane *i* (veh/h/ln, Chapter 30)

V_i demand volume for movement *i* (veh/h)

v_i' demand flow rate (veh/cycle/ln)

v_{i1} major-street through vehicles in shared lane (veh/h)

v_{i2} major-street turning vehicles in shared lane (veh/h)

$v_{i,ATS}$ demand flow rate i for ATS estimation (pc/h)

$v_{i,j}$ volume entering from origin i and exiting at destination j (veh/h)

$v_{i,pce}$ demand flow rate for movement i (pc/h)

$v_{i,PTSF}$ demand flow rate i for determination of PTSF (pc/h)

$V_{i,t}$ demand flow rate on section i during analysis period t (veh/h)

v_{i1} major-street through-movement flow rate (veh/h)

v_{i2} major-street right-turn flow rate (veh/h)

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

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

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

V_{iq} vehicle-in-queue count (veh)

v_j demand flow rate of movement j (veh/h)

v_l left-turn flow rate using a given entry (veh/h, Chapter 22); demand flow rate in exclusive left-turn lane group (veh/h/ln, Chapter 31)

v_L major left-turn or U-turn flow rate (veh/h, Chapter 20); O-D demand flow rate traveling through the first intersection and turning left at the second (Chapter 23)

v_{L+TH} through and left-turn movement combined flow rate (veh/h)

v_{LL} demand flow rate in left lane (veh/h)

v_{lr} demand flow rate in shared left- and right-turn lane group (veh/h)

v_{lt} left-turn demand flow rate (veh/h, Chapter 19); lane flow rate for the left-turn lane group (tpc/h/ln, Chapter 31)

$v_{lt,perm}$ permitted left-turn demand flow rate (veh/h)

$v_{lt,pt}$ lane flow rate for the left-turn lane group during the protected left-turn phase (tpc/h/ln)

v_m midsegment demand flow rate (veh/h, Chapter 18); flow rate for mode m (SUT/h, TT/h, or pc/h; Chapter 26)

$VM(t)$ volume on upstream section for analysis period t (veh/h)

v_{mi} adjusted midsegment demand flow rate (veh/h)

V_{max} maximum achievable segment speed (mi/h)

v_{mg} merge flow rate (veh/h/ln)

v_{mix} flow rate of mixed traffic (veh/h/ln)

$VMT(t, d)$ vehicle miles traveled during time period t measured at lane detector station d

VMT_i vehicle miles traveled for segment i (veh-mi)

VMT_{i15} total vehicle miles traveled by all vehicles in directional segment i during the 15-min analysis period (veh-mi)

VMT_j average vehicle miles traveled for scenarios in month j

VMT_{Seed} vehicle miles of travel in the seed file

$VMT_{seg,u}$ vehicle miles traveled on segment seg during analysis period u in the seed file

VMT_t facility vehicle miles traveled during time period t

$VMT_{t,d}$ vehicle miles traveled during time period t measured at lane detector station d

v_n flow rate for the outside lane (veh/h/ln)

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

v_o opposing demand flow rate (veh/h)

$v_{o,ATS}$ demand flow rate for ATS determination in the opposing direction (pc/h)

$v_{o,PTSF}$ demand flow rate in the opposing direction for estimation of PTSF (pc/h)

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

v_{OD} O-D demand volumes (veh/h)

$v_{od,i,j,k}$ volume entering from origin i and exiting at destination j for subperiod k (veh/h)

$V_{OFF15ij}$ 15-min exit count for time period i and exiting location j (veh)

v_{OL} directional demand flow rate in the outside lane (veh/h)

V_{ON15ij} 15-min entering count for time period i and entering location j (veh)

v_p demand flow rate under equivalent base conditions (pc/h/ln, Chapter 12); pedestrian flow per unit width (p/ft/min, Chapter 18); pedestrian flow rate (p/s, Chapter 20)

v_{ped} unit flow rate (p/min/ft, Chapter 4); pedestrian flow rate in the subject sidewalk (walking in both directions) (p/h, Chapter 18)

$v_{ped,i}$ pedestrian flow rate in the subject crossing for travel direction i (p/h)

v_{pedg} pedestrian flow rate during the pedestrian service time (p/h)

v_r demand flow rate in exclusive right-turn lane group (veh/h/ln)

v_R flow rate on the on-ramp or off-ramp (pc/h, Chapter 14); right-turn movement flow rate (veh/h, Chapter 20); right-turn flow rate using a given entry (veh/h, Chapter 22); O-D demand flow rate traveling through the first intersection and turning right at the second (Chapter 23); ramp flow feeding subject queue (veh/h, Chapter 23)

V_R ratio of weaving demand flow rate to total demand flow rate in the weaving segment (decimal)

VR volume ratio (decimal)

$VR(t)$ volume on ramp during analysis period t (veh/h)

$v_{R,e}$ nonbypass right-turn flow rate using a given entry (veh/h)

v_{R12} sum of the flow rates in Lanes 1 and 2 and the ramp flow rate (on-ramps only) (pc/h)

$v_{Ramp\text{-}L}$ upstream ramp left-turning flow (veh/h)

v_{RF} ramp-to-freeway demand flow rate in the weaving segment (pc/h)

v_{RL} demand flow rate in right lane (veh/h)

v_{RR} ramp-to-ramp demand flow rate in the weaving segment (pc/h)

v_{rt} right-turn demand flow rate (veh/h)

v_{rtor} right-turn-on-red flow rate (veh/h)

v_s transit frequency for the segment (veh/h)

v_{sep} flow rate for the movement considered as a separate lane (veh/h)

v_{sl} demand flow rate in shared left-turn and through lane group (veh/h)

$v_{sl,i,j,k}$ demand flow rate in shared left-turn and through lane group j at intersection i for subperiod k (veh/h)

$v_{sl,lt}$ left-turn flow rate in shared lane group (veh/h/ln)

v_{sr} demand flow rate in shared right-turn and through lane group (veh/h)

$v_{sr,i,j,k}$ demand flow rate in shared right-turn and through lane group j at intersection i for subperiod k (veh/h)

$v_{sr,rt}$ right-turn flow rate in shared lane group (veh/h/ln)

v_t demand flow rate in exclusive-through lane group (veh/h/ln, Chapter 18); through flow rate using a given entry (veh/h, Chapter 22)

v_T right-turn flow rate using a given entry (veh/h, Chapter 22); O-D demand flow rate traveling through the first intersection and through the second (Chapter 23)

$v_{t,i,j,k}$ demand flow rate in exclusive-through lane group j at intersection i for subperiod k (veh/h/ln)

v_{th} through-demand flow rate (veh/h)

V_{tot} total number of vehicles arriving during the survey period (veh)

v_U flow rate on the adjacent upstream ramp (pc/h, Chapter 14); U-turn flow rate (veh/h, Chapter 22)

v_{vph} one-direction demand flow rate (veh/h)

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

$V_{W,start}$ starting shock wave speed for arterial through movements due to the downstream queue (ft/s)

$V_{W,stop}$ stopping shock wave speed for arterial through movements due to the downstream queue (ft/s)

v_x flow rate for movement x (veh/h, Chapter 20); number of groups of pedestrians, where x is Movement 13, 14, 15, or 16 (Chapter 20)

v_y flow rate of the y movement in the subject shared lane (veh/h)

w lane width of the lane that the minor movement is negotiating into (ft)

W weaving intensity factor (Chapter 13); width of the clear zone for the longest vehicle path, measured along the centerline of the outside lane (ft, Chapter 23); effective width of crosswalk (ft, Chapter 31)

W_a effective width of Sidewalk A (ft)

W_A available sidewalk width (ft)

W_{aA} adjusted available sidewalk width (ft)

Walk pedestrian walk setting (s)

Walk_{mi} pedestrian walk setting for the phase serving the minor-street through movement (s)

W_b effective width of Sidewalk B (ft)

W_{bl} width of the bicycle lane (ft)

W_{buf} buffer width between roadway and sidewalk (ft)

w_c average width of circulating lane(s) (ft)

W_c crosswalk width (ft)

W_{cd} curb-to-curb width of the cross street (ft)

W_d effective width of Crosswalk D (ft)

W_e effective width of the outside through lane (ft)

W_E effective sidewalk or walkway width (ft)

W_i width of signalized intersection as measured along the segment centerline (ft)

$w_{i,j,k}$ weighting factor for lane group j at intersection i for subperiod k (veh)

W_l total width of shoulder, bicycle lane, and parking lane (ft)

W_O sum of fixed-object effective widths and linear-feature shy distances at a given point along the walkway (ft)

$W_{O,i}$ adjusted fixed-object effective width on inside of sidewalk (ft)

$W_{O,o}$ adjusted fixed-object effective width on outside of sidewalk (ft)

W_{ol} width of the outside through lane (ft)

W_{OL} outside lane width (ft)

W_{os} width of paved outside shoulder (ft)

W_{os}^* adjusted width of paved outside shoulder (ft)

W_{pk} width of striped parking lane (ft)

w_q queue change rate (veh/s)

W_s paved shoulder width (ft)

$WS(i, p)$ wave speed: speed at which a front-clearing queue shock wave travels through segment i during time interval p (ft/s)

$W_{s,i}$ shy distance on inside of sidewalk (ft)

$W_{s,o}$ shy distance on outside of sidewalk (ft)

W_t total width of the outside through lane, bicycle lane, and paved shoulder (ft)

W_T total walkway width (ft)

$w_{thru,m,k}$ weighting factor for site m for subperiod k (veh)

WTT wave travel time (time steps)

$WTT(i, p)$ wave travel time: time taken by the shock wave traveling at wave speed WS to travel from the downstream end of segment i to the upstream end of the segment during time interval p (time steps)

$WTT_{b,i}$ travel-time-weighted average bicycle LOS score for segment i

$WTT_{p,i}$ travel-time-weighted average pedestrian LOS score for segment i

W_v effective total width of outside through lane, bicycle lane, and shoulder as a function of traffic volume (ft)

x volume-to-capacity ratio of the link's rightmost lane on a roundabout approach (Chapter 18); degree of utilization (Chapter 21); volume-to-capacity ratio of the subject lane (Chapter 22); distance from average bicyclist to user (mi, Chapter 24)

X peak hour volume-to-capacity ratio (decimal, Chapter 11); volume-to-capacity ratio (Chapter 20); distance of user beyond end of path segment (mi, Chapter 24)

X_1 volume-to-capacity ratio in the shared lane
X_A average volume-to-capacity ratio
X_c critical intersection volume-to-capacity ratio
x_{CL} degree of utilization on the conflicting approach from the left
x_{clear} distance between the DDI crossover stop bar and the yield conflict point (ft)
x_{CR} degree of utilization on the conflicting approach from the right
X_i volume-to-capacity ratio for lane or lane group i
$x_{i,1+2}$ combined degree of saturation for the major-street through and right-turn movements
x_O degree of utilization on the opposing approach
X_u weighted volume-to-capacity ratio for all upstream movements contributing to the volume in the subject movement group
y flow ratio (Chapter 19); intermediate calculation variable (Chapter 20)
y^* flow ratio for the approach
Y yellow change interval (s, Chapter 19); yellow-plus-all-red change-and-clearance interval (s, Chapter 23)
y_3 effective flow ratio for concurrent (or transition) Phase 3
y_7 effective flow ratio for concurrent (or transition) Phase 7
Y_c sum of the critical flow ratios
$Y_{c,I}$ sum of the critical flow ratios for Intersection I
$Y_{c,II}$ sum of the critical flow ratios for Intersection II
$y_{c,i}$ critical flow ratio for phase i
$Y_{c,max}$ sum of the critical flow ratios for the interchange
Y_{mi} change interval of the phase serving the minor-street through movement (s)
YP_2 yield point for Phase 2 (s)
y_t effective flow ratio for the concurrent phase when dictated by travel time
z percentile parameter
α fraction of capacity drop in queue discharge conditions due to congestion on the facility
α_{wz} percentage drop in prebreakdown capacity at the work zone due to queuing conditions (%)
β shape parameter of the fitted Weibull distribution
β_1 model coefficient for 2-to-1 lane closures
β_2 model coefficient for 2-to-2 lane closures
β_3 model coefficient for 3-to-2 lane closures
β_4 model coefficient for 4-to-3 lane closures
β_5 model coefficient for volume ratio
β_6 model coefficient for auxiliary lane length
γ scale parameter of the fitted Weibull distribution
δ slope of the travel time–versus–distance curve (s/ft)
δ_1 adjustment parameter for incident frequency
δ_2 adjustment parameter for incident severity
δ_3 adjustment parameter for incident duration
δ_4 adjustment parameter for incident location
δ_5 adjustment parameter for incident start time
Δ headway of bunched vehicle stream (s/veh)
Δ^* equivalent headway of bunched vehicle stream served by the phase (s/veh)
Δ_i headway of bunched vehicle stream in lane group i (s/veh)
$\Delta_{RO_{i,t}}$ additional oversaturation delay rate for segment i at analysis period t (min/mi)
$\Delta_{RU_{i,t}}$ delay rate for segment i in time period t (min/mi)
$\Delta\tau_{TI}$ traffic interaction term (s/mi)

λ threshold breakdown rate (Chapter 26); flow rate parameter (veh/s) (Chapter 30)

λ^* flow rate parameter for the phase (veh/s)

λ_{A2} rate of change in A_2 per unit increase in free-flow speed (mi/h)

λ_{BP} rate of increase in breakpoint per unit decrease in free-flow speed (pc/h/ln)

λ_c rate of change in capacity per unit change in free-flow speed (pc/h/ln)

$\lambda_{c,i}$ flow rate parameter for lane group *i* served in the concurrent phase that also ends at the barrier (veh/s)

λ_i flow rate parameter for lane group *i*

λ_l flow rate parameter for the exclusive left-turn lane group (veh/s)

λ_r flow rate parameter for the exclusive right-turn lane group (veh/s)

λ_{sl} flow rate parameter for shared left-turn and through lane group (veh/s)

λ_{sr} flow rate parameter for shared right-turn and through lane group (veh/s)

λ_t flow rate parameter for exclusive-through lane group (veh/s)

μ_i average speed of mode *i* (mi/h)

$\rho_{g,\mathrm{mix}}$ coefficient for grade term in the mixed-flow CAF equation (decimal)

σ_{spot} standard deviation of spot speeds (mi/h)

τ_a automobile free-flow travel rate (s/mi)

$\tau_{f,A,j}$ end-of-grade spot travel time rate for automobiles (s/mi)

$\tau_{f,SUT,j}$ spot travel time rate for SUTs at the end of segment *j* (s/mi)

$\tau_{f,SUT,kin,j}$ spot kinematic travel time rate of SUTs at the end of segment *j* (s/mi)

$\tau_{f,TT,j}$ spot travel time rate for TTs at the end of segment *j* (s/mi)

$\tau_{f,TT,kin,j}$ spot kinematic travel time rate of TTs at the end of segment *j* (s/mi)

τ_{kin} kinematic space-based travel time rate (s/mi)

τ_m travel time rate for mode *m* (s/mi)

$\tau_{\mathrm{mix},j}$ mixed-flow space-based travel time rate for segment *j* (s/mi)

$\tau_{S,A,j}$ automobile space-based travel time rate (s/mi)

$\tau_{S,SUT,j}$ space-based travel time rate for SUTs across segment *j* (s/mi)

$\tau_{S,SUT,kin,j}$ kinematic space-based travel time rate of SUTs (s/mi)

$\tau_{S,TT,j}$ space-based travel time rate for TTs across segment *j* (s/mi)

$\tau_{S,TT,kin,j}$ kinematic space-based travel time rate of TTs (s/mi)

τ_{SUT} SUT free-flow travel rate (s/mi)

$\tau_{SUT,10000}$ travel time rate for a SUT at a point 10,000 ft along the upgrade (s/mi)

$\tau_{SUT,kin}$ kinematic travel rate of SUTs (s/mi)

τ_{TT} TT free-flow travel rate (s/mi)

$\tau_{TT,10000}$ travel time rate for a TT at a point 10,000 ft along the upgrade (s/mi)

$\tau_{TT,kin}$ kinematic travel rate of TTs (s/mi)

φ^* combined proportion of free (unbunched) vehicles for the phase (decimal)

φ_i proportion of free (unbunched) vehicles in lane group *i* (decimal)

ϕ_{mix} exponent for the speed–flow curve (decimal)

VOLUME 1 INDEX

The index to Volume 1 lists the text citations of the terms defined in the Glossary (Volume 1, Chapter 9). Volumes 1, 2, and 3 are separately indexed. In the index listings, the first number in each hyphenated pair of numbers indicates the chapter, and the number after the hyphen indicates the page within the chapter.

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