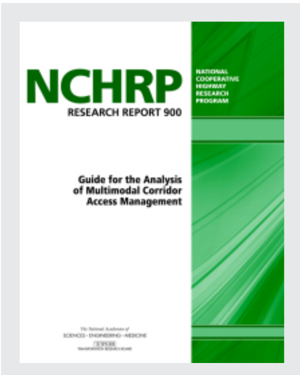


Guide for the Analysis of Multimodal Corridor Access Management (2018)

DETAILS

128 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-48003-1 | DOI 10.17226/25342

CONTRIBUTORS

Marc Butorac, James Bonneson, Kristine Connolly, Paul Ryus, Bastian Schroeder, Kristine Williams, Zhenyu Wang, Seckin Ozkul, and Jerome Gluck; National Cooperative Highway Research Program; Transportation Research Board; National Academies of Sciences, Engineering, and Medicine

SUGGESTED CITATION

National Academies of Sciences, Engineering, and Medicine 2018. *Guide for the Analysis of Multimodal Corridor Access Management*. Washington, DC: The National Academies Press. https://doi.org/10.17226/25342.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

NCHRP RESEARCH REPORT 900

Guide for the Analysis of Multimodal Corridor Access Management

Marc Butorac
James Bonneson
Kristine Connolly
Paul Ryus
Bastian Schroeder
Kittelson & Associates, Inc.
Portland, OR

Kristine Williams
Zhenyu Wang
Seckin Ozkul
Center for Urban Transportation Research
University of South Florida
Tampa, FL

Jerome Gluck
AECOM, Inc.
New York, NY

Subscriber Categories
Pedestrians and Bicyclists • Operations and Traffic

Research sponsored by the American Association of State Highway and Transportation Officials
in cooperation with the Federal Highway Administration

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRB
TRANSPORTATION RESEARCH BOARD

2018

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

Systematic, well-designed, and implementable research is the most effective way to solve many problems facing state departments of transportation (DOTs) administrators and engineers. Often, highway problems are of local interest and can best be studied by state DOTs individually or in cooperation with their state universities and others. However, the accelerating growth of highway transportation results in increasingly complex problems of wide interest to highway authorities. These problems are best studied through a coordinated program of cooperative research.

Recognizing this need, the leadership of the American Association of State Highway and Transportation Officials (AASHTO) in 1962 initiated an objective national highway research program using modern scientific techniques—the National Cooperative Highway Research Program (NCHRP). NCHRP is supported on a continuing basis by funds from participating member states of AASHTO and receives the full cooperation and support of the Federal Highway Administration, United States Department of Transportation.

The Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine was requested by AASHTO to administer the research program because of TRB's recognized objectivity and understanding of modern research practices. TRB is uniquely suited for this purpose for many reasons: TRB maintains an extensive committee structure from which authorities on any highway transportation subject may be drawn; TRB possesses avenues of communications and cooperation with federal, state, and local governmental agencies, universities, and industry; TRB's relationship to the National Academies is an insurance of objectivity; and TRB maintains a full-time staff of specialists in highway transportation matters to bring the findings of research directly to those in a position to use them.

The program is developed on the basis of research needs identified by chief administrators and other staff of the highway and transportation departments, by committees of AASHTO, and by the Federal Highway Administration. Topics of the highest merit are selected by the AASHTO Special Committee on Research and Innovation (R&I), and each year R&I's recommendations are proposed to the AASHTO Board of Directors and the National Academies. Research projects to address these topics are defined by NCHRP, and qualified research agencies are selected from submitted proposals. Administration and surveillance of research contracts are the responsibilities of the National Academies and TRB.

The needs for highway research are many, and NCHRP can make significant contributions to solving highway transportation problems of mutual concern to many responsible groups. The program, however, is intended to complement, rather than to substitute for or duplicate, other highway research programs.

NCHRP RESEARCH REPORT 900

Project 03-120
ISSN 2572-3766 (Print)
ISSN 2572-3774 (Online)
ISBN 978-0-309-48003-1
Library of Congress Control Number 2018964970

NOTICE

The research report was reviewed by the technical panel and accepted for publication according to procedures established and overseen by the Transportation Research Board and approved by the National Academies of Sciences, Engineering, and Medicine.

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research and are not necessarily those of the Transportation Research Board; the National Academies of Sciences, Engineering, and Medicine; or the program sponsors.

The Transportation Research Board; the National Academies of Sciences, Engineering, and Medicine; and the sponsors of the National Cooperative Highway Research Program do not endorse products or manufacturers. Trade or manufacturers' names appear herein solely because they are considered essential to the object of the report.

Published research reports of the

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

are available from

Transportation Research Board
Business Office
500 Fifth Street, NW
Washington, DC 20001

and can be ordered through the Internet by going to

http://www.national-academies.org

and then searching for TRB

Printed in the United States of America

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, non-governmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. C. D. Mote, Jr., is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.national-academies.org**.

The **Transportation Research Board** is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to increase the benefits that transportation contributes to society by providing leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied committees, task forces, and panels annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

Learn more about the Transportation Research Board at **www.TRB.org**.

C O O P E R A T I V E R E S E A R C H P R O G R A M S

CRP STAFF FOR NCHRP RESEARCH REPORT 900

NCHRP PROJECT 03-120 PANEL
Field of Traffic—Operations and Control

AUTHOR ACKNOWLEDGMENTS

The research reported herein was performed under NCHRP Project 03-120, "Assessing Interactions Between Access Management Treatments and Multimodal Users". Kittelson & Associates, Inc. (KAI) was the contractor for this study. The Center for Urban Transportation Research, University of South Florida (CUTR), and AECOM, Inc. were subcontractors. Authors of this report are Marc Butorac, James Bonneson, Kristine Connolly, Paul Ryus, and Bastian Schroeder (KAI); Kristine Williams, Zhenyu Wang, and Seckin Ozkul (CUTR); and Jerome Gluck (AECOM, Inc.). Mr. Butorac served as the principal investigator for this project.

The authors acknowledge the assistance and support of key staff members for their significant contributions to the data collection and traffic simulation tasks. The KAI staff members include Elizabeth Connell, Chelsea Farnsworth, Ellen Moshier, Clarissa Dougherty, Miranda Barrus, and Lake Trask. The CUTR graduate research assistants and staff members include Dharmin Kukadia, Teerapat Charukitpaisarn, Abhijit Vasili, Rama Durga Tammayya Naidu Kolla, and Ashok Sampath. The AECOM, Inc. staff members include Jacquilyn Coelho, Gabriel Kleinfeld, Jeffrey Sandberg, and Chaithra Jagadish.

The authors extend special thanks to the agency staff who provided assistance during the data collection tasks. Those individuals include Ping P. Hsu and Richard Napora (Florida Department of Transportation, District 7) and Norman D. Jester (Pinellas County, Florida). The authors also acknowledge Li Zhang and Xiang Li from New Global Systems for technical support in implementing the Surrogate Safety Assessment Model (version 3.0) and express sincere thanks to the members of the project panel, who provided extremely helpful guidance and feedback on the many documents they were asked to review.

FOREWORD

By Waseem Dekelbab
Staff Officer
Transportation Research Board

NCHRP Research Report 900 will assist in the selection of alternative access management techniques based on the safety and operation performance of each affected travel mode. The guide documents operational and safety relationships between access management techniques and the automobile, pedestrian, bicycle, public transit, and truck modes. The analyses in the guide generally reflect a suburban and urban land use context. This report will be of immediate interest to practitioners involved in how to weigh, evaluate, and understand the effects and trade-offs when implementing access management techniques in a multimodal corridor.

The roadway system must accommodate many types of users—bicyclists, passenger cars, pedestrians, transit, and trucks. Increasingly, stakeholders are recognizing that there should be an appropriate balance between the various modes. Access connections to the roadway are a part of the system, and there is increasing recognition that the location and design of access to and from roadways affect all transportation modes. There is a need to understand better the interactions between multimodal operations and access management techniques and treatments, and the trade-off decisions that are necessary. In addition, suburban and urban land uses continually change, and access management planning for retrofitting corridors should consider the multimodal needs as well as the need to upgrade arterial performance. Past studies have shown that arterial roadway characteristics such as turning movements, unsignalized and signalized access density, median type, turn lanes, sidewalks, bike lanes, and bus turnouts can all affect corridor operations.

Studies have also shown that effective access management treatments reduce conflict points along roadways, leading to reductions in delays and crashes. However, there has been limited understanding of the effects of access management treatments on multimodal operations, and vice versa, particularly treatments in combination. As a result, quantitative relationships to assess measures of effectiveness of access management techniques and multimodal interactions for, but not limited to, average travel speed, travel time reliability, and capacity preservation are needed.

Under NCHRP Project 03-120, "Assessing Interactions Between Access Management Treatments and Multimodal Users," Kittelson & Associates, Inc., was asked to identify and determine unknown relationship definitions between access management techniques and the various users and modes along multimodal corridors. Performance relationships and priorities may differ under a central business district context, and the guide does not supersede engineering judgment by the knowledgeable design professional. Specific combinations of characteristics in other environments may produce outcomes that differ from those presented herein. The fact that new operational and safety performance relationships are presented does not imply that existing roadways or highways are unsafe nor does it mandate the initiation of improvement projects.

The research agency's final report, which documents the entire research effort, is available for download from TRB's website at www.trb.org by searching *NCHRP Web-Only Document 256: Assessing Interactions Between Access Management Treatments and Multimodal Users.*

CONTENTS

Note: Photographs, figures, and tables in this report may have been converted from color to grayscale for printing. The electronic version of the report (posted on the web at www.trb.org) retains the color versions.

SUMMARY

Guide for the Analysis of Multimodal Corridor Access Management

This guide summarizes available knowledge on the interactions of more than 70 access management techniques with the operations and safety of motorized vehicles, pedestrians, bicyclists, buses, and trucks. Where they are available, quantitative tools are identified and described that can be used to evaluate the magnitude of the interaction on a specific travel mode. In other cases, no quantitative tools exist, but qualitative relationships are documented in the literature. These qualitative relationships are also summarized in the guide. Finally, no research has been performed on the interaction between a specific access management technique and a specific mode. This lack of knowledge is also documented in the guide and can serve as a starting point for identifying future research needs.

This guide has been written for access management practitioners who already have some familiarity with the range of potential access management techniques. The guide extends the information provided in the *Access Management Manual,* Second ed. (*1*) and the *Access Management Application Guidelines* (*2*) to present current knowledge about the multimodal effects of access management techniques. However, the guide does not intend to duplicate information found in these two basic references. To help readers learn more about how to implement specific access management techniques, each section of the guide provides cross-references to specific sections of the *Access Management Manual* and *Access Management Application Guidelines,* along with other relevant reports that provide additional information.

Defining Operational and Safety Performance

Operational performance reflects the ease with which a traveler can move along a roadway. *Safety performance* reflects the chances of a traveler being involved in a crash or a close call while on the roadway. A small number of performance measures are commonly used to describe operational and safety performance; these measures are described as follows.

Common Operational Performance Measures

Motorized Travel Modes (Automobile, Bus, and Truck)

These operational performance measures frequently describe the operations of motorized travel modes:

- **Delay.** Extra travel time required to travel along the street compared with the time required to travel at the posted or free-flow speed. Delay can be caused by waiting for a red light to change at a traffic signal, waiting for a gap in traffic to turn onto a street, and being stuck behind a vehicle waiting to make a turn, among other causes. For buses, delay can also occur when a bus has to wait for a gap in traffic before it can proceed down the street after serving a bus stop.

- **Travel speed.** The speed that vehicles drive along the street. This speed can be expressed as an *average travel speed* that includes delays, or as a *free-flow speed,* an average midblock travel speed without delays, under low-traffic-volume conditions.
- **Stopping rate.** The average number of times per mile that a vehicle must come to a stop. This measure is particularly relevant to buses and trucks, which take more time than automobiles to accelerate back to their running speed and therefore experience more delay with every stop, compared with automobiles.
- **Queue length.** The length of a line of stopped vehicles (for example, waiting for a green light or waiting for a gap in traffic to make a turn). This length is often expressed as a 95th percentile length—the maximum length observed or expected once every 20 times—for the purposes of sizing turn lanes and locating driveways. Queues that spill out of a turn lane into a through travel lane or that block driveways can cause both operational and safety problems.
- **Level of service.** Speed and delay can also be expressed as a *level of service* (LOS), a letter A (best) to F (worst) that is assigned to ranges of speeds or delays according to tables provided in the *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis* (HCM6) (*3*).

Improvements in motorized vehicle operational performance are characterized by reduced delay, increased travel speeds, fewer stops, shorter queues, or improved levels of service. Note that an improvement in a given mode's operational performance is not always the desired outcome in the bigger picture; for example, faster auto travel speeds are typically associated with reduced bicycle and pedestrian operational performance (level of service) and, depending on the circumstances, may result in reduced safety performance for one or more travel modes.

Non-Motorized Travel Modes (Pedestrian and Bicycle)

These operational performance measures frequently describe the operations of non-motorized travel modes:

- **Delay.** Extra travel time required to travel along the street. Delay can be caused by waiting for a walk signal at a crosswalk, waiting for a gap in traffic to cross a street, or extra travel time required when forced to travel out of direction.
- **Level of service.** The HCM6 defines pedestrian and bicycle LOS as a function of a number of factors, including the quality of the pedestrian/bicycle infrastructure, motorized traffic volumes and speeds, and parking presence, among others (see the appendix for more details). LOS can be expressed as a numerical value that is the average level of satisfaction that pedestrians or bicyclists would rate the facility or intersection. These scores can also be converted into A (best) to F (worst) letters using tables in the HCM6.

Improved pedestrian operational performance and bicycle operational performance are characterized by reduced delay or improved level of service.

Common Safety Performance Measures

These safety performance measures frequently describe the safety of various travel modes:

- **Crash rate.** The number of crashes per number of vehicles or distance traveled (e.g., crashes per million vehicles entering an intersection or crashes per million vehicle miles

traveled on a roadway). Because the number of crashes increases with traffic volume, crash rates are used to compare different roadways on an apples-to-apples basis, by accounting for the different traffic volumes on the two roadways.
- **Conflict points.** Conflict points are locations where the paths of two vehicles can cross. The greater the number of turning movements allowed at an intersection or driveway, the greater the opportunity for two vehicles to come in conflict with each other, and the greater the potential for drivers to make mistakes (*1*).
- **Conflicts.** Some types of crashes, such as those involving pedestrians and bicyclists, are relatively rare but very serious when they do occur. Because of the relatively low number of these types of crashes, it can be difficult for research to quantify the change in crash rate expected to result from applying a particular access management technique. Instead, some research has investigated the change in the number of conflicts (e.g., near misses, sudden maneuvers, or hard braking) that occur following the use of a particular technique.

Improved safety performance is characterized by reduced crash rates, reduced number of conflict points, or reduced number of conflicts.

Organization of the Guide

Overview

Each chapter addresses one of 19 groups of related access management techniques, with each group containing between one and eight techniques. Each of these techniques, with the exception of installing a roundabout in lieu of a traffic signal, has been described in *NCHRP Report 420*: *Impacts of Access Management Techniques* (*4*). Each chapter is organized similarly, with information presented in order from the most general (performance summaries) to more detailed (qualitative descriptions of performance trends) to the most detailed (descriptions of available tools for quantifying specific operations and safety interactions by mode). Finally, an appendix provides detailed guidance on applying the most common tools available for quantifying the interactions of access management techniques.

Access Management Technique Groups

The 19 groups of techniques covered in the guide consist of the following access management technique groups presented in consecutive chapters:

Chapter 1	Restrict Left-Turn Movements at an Access Point
Chapter 2	Non-Traversable Medians
Chapter 3	Continuous Two-Way Left-Turn Lanes
Chapter 4	Frontage and Service Roads
Chapter 5	Unsignalized Median Openings
Chapter 6	Traffic Signal Spacing
Chapter 7	Number and Spacing of Unsignalized Access Points
Chapter 8	Interchange Areas
Chapter 9	Left-Turn Lanes
Chapter 10	Right-Turn Lanes
Chapter 11	Driveway Channelization
Chapter 12	Alternative Intersections and Interchanges
Chapter 13	Parking and Stopping Restrictions
Chapter 14	Roundabouts
Chapter 15	Driveway Sight Distance
Chapter 16	One-Way Driveways

Description

Each chapter begins with a general description of the characteristics of the techniques included in that group as well as a representative photograph.

Multimodal Operations and Safety Performance Summary

The table below summarizes general performance trends and documented performance relationships associated with each access management technique in the group. The table is organized by technique, travel mode, and the areas of operations and safety. Hollow dots indicate combinations of techniques and travel modes for which no performance relationship has been documented. All other symbols indicate the existence of a relationship for that combination of technique and mode.

Possible general performance trends are improved performance, decreased performance, mixed performance, unchanged performance, and no relationship documented. The mixed performance category is used when (*a*) a technique produces both positive and negative interactions with a particular mode or (*b*) a technique in some cases has no interaction and in other cases has an interaction. The unchanged performance category is used when the interaction has been studied and no change in performance was documented. Performance trends are generally associated with a suburban/urban land use context and may differ under a central business district context for certain access management techniques. The two possible types of documented relationships are quantitative and qualitative.

The performance trend information presented in Table 1 does not indicate the magnitude of the interaction, either by itself or relative to other techniques. In some cases, the answer depends on other factors. Consult the detailed information presented later in each chapter to make these determinations.

Entries for motor vehicles (i.e., the car symbol) are based on the cited research that may be specific to only passenger cars or, more broadly, representative of all forms of motor vehicles, including trucks, buses, and so forth. To understand the specific context, readers should consult the cited research to identify the specific performance trends.

Table 1. Multimodal operations and safety performance summary.

	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
Access Management Technique	🚗	🚶	🚲	🚌	🚚	🚗	🚶	🚲	🚌	🚚
Install continuous TWLTL.	↑ ●	↓ ●	↓ ●	↕ ●	↑ ●	↕ ●	↓ ●	↓ ◐	○	○

Note for multimodal operations and safety performance summary tables:
○ = no relationship documented.
General performance trends: ↑ = improved performance, ↓ = decreased performance, and ↕ = mixed performance.
Documented performance relationships: ● = quantitative relationship and ◐ = qualitative relationship.
Performance trends are associated with a suburban/urban land use context and may differ under a central business district context.
Entries for buses and trucks indicate relationships specific to those modes; motor vehicle relationships also apply.

Entries for the bus and truck modes reflect interactions specific to those modes. However, buses and trucks are also types of motor vehicles; therefore, the information presented for motor vehicles in general also applies to buses and trucks. Nevertheless, in some cases, the magnitude of a particular interaction may be different for buses and trucks from motor vehicles in general. Buses or trucks may experience additional interactions that motor vehicles do not. These differences are reflected in the entries in the bus and truck columns of the tables.

General Trends Associated with Improvements

Each chapter has a table that describes the documented interactions between access management techniques and a given mode's operations and safety. Sources are also listed.

Quantitative Analysis Methods

Where one or more quantitative analysis methods exist for a given combination of mode and operations or safety, this subsection provides information about those methods. For relatively simple methods, such as crash modification factors, the specific relationship is presented in the text, along with a reference to the source document. For complex methods (e.g., methods found in the HCM6), this subsection provides a reference to the source document and provides guidance on the potential magnitude of the relationship. The appendix provides additional guidance on quantitative methods that appear in multiple guide sections.

Additional Information

This subsection provides cross-references to additional sources of information about this group of 19 access management techniques. These sources include the following:

- Other chapters in this guide.
- Specific chapters and sections within the *Access Management Manual,* Second ed.
- Specific chapters and sections within the *Access Management Application Guidelines.*
- NCHRP reports and other authoritative documents.

References

1. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
2. Dixon, K. K., R. D. Layton, M. Butorac, P. Ryus, J. L. Gattis, L. Brown, and D. Huntington. *Access Management Application Guidelines.* Transportation Research Board, Washington, D.C., 2016.
3. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
4. Gluck, J., H. S. Levinson, and V. Stover. *NCHRP Report 420: Impacts of Access Management Techniques.* Transportation Research Board, Washington, D.C., 1999.

CHAPTER 1

Restrict Left-Turn Movements at an Access Point

Source: Photograph provided by the authors.

Description

Techniques in this group eliminate or reduce left-turn movements through a range of actions, including physically precluding left turns by constructing a non-traversable median and prohibiting left turns by installing regulatory signage. Vehicles that previously made a direct left turn must make a right turn followed by a U-turn (if exiting the access) or a U-turn followed by a right turn (if entering the access). The U-turns can be made at downstream intersections or at U-turn crossovers developed in the roadway median.

Tables 2 and 3 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

A study in Florida (*6*) found that making a right turn followed by a U-turn at a downstream median opening was faster on average than making a direct left turn, accounting for the extra travel time involved, under the following conditions on 6- and 8-lane arterials:

- > 5,500 vehicles/hour (sum of both directions) on the arterial and 50 vehicles/hour exiting the driveway;
- > 5,200 vehicles/hour on the arterial and 100 vehicles/hour exiting the driveway; and
- > 5,000 vehicles/hour on the arterial and 150 vehicles/hour exiting the driveway.

Table 2. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
	[car]	[pedestrian]	[bicycle]	[bus]	[truck]	[car]	[pedestrian]	[bicycle]	[bus]	[truck]
Close existing median openings.	↕ ●	○	↓ ◐	○	○	↑ ◐	↑ ◐	↑ ◐	○	○
Replace full median opening with one serving only left turns from the major roadway.	↕ ●	○	○	○	○	↑ ◐	○	○	○	○
Install U-turn crossovers in conjunction with left-turn restrictions.	↑ ●	↕ ◐	○	↓ ◐	↕ ◐	↑ ●	○	○	○	○
Prohibit left turns through signage, channelizing islands, or both.	↑ ●	○	○	○	○	↕ ◐	↕ ◐	↕ ◐	○	○
Prohibit left turns into driveways on undivided highways.	↑ ●	○	○	○	○	↕ ◐	↕ ◐	↕ ◐	○	○

Table 3. General trends associated with restricting left turns at an access point.

Mode	Operations	Safety
[car]	At higher traffic volumes and with diversion distances under 0.5 mile, the total time taken to make a right turn followed by a U-turn can be less than the time required for a direct left turn (*1*, *2*), when the left turn is made in one continuous movement. A U-turn crossover can be signalized without impairing traffic progression (*1*).	Reduces the number and location of conflict points (*2*). Median U-turn intersections, which require similar movements, typically experience 20–50% fewer crashes relative to full-movement intersections (*3*). Vehicles may violate left-turn restrictions enforced only by signs, channelizing islands, or both (*1*, *2*).
[pedestrian]	Back-to-back signalized U-turn crossovers provide an opportunity to create a signalized midblock pedestrian crossing.	Reduces the number of conflicts turning motorists must observe at a given time. Motorists making left turns from TWLTL lanes and undivided roadways may speed up when a pedestrian is approaching a driveway (*4*).
[bicycle]	May require out-of-direction travel for bicycles exiting the access. Design unsignalized U-turn crossovers such that vehicles can make the U-turn without encroaching on a bicycle lane.	Reduces the number of conflicts turning motorists must observe at a given time.
[bus]	U-turn crossovers preclude placing a midblock bus stop in the travel lane at or just downstream of the crossover (*5*).	No documented effect beyond that generally observed for motor vehicle traffic.
[truck]	A “loon” (widened pavement area on the edge of the roadway) or “bulb” may need to be constructed to accommodate U-turning trucks with large turning radii at locations with narrow medians (*3*).	No documented effect beyond that generally observed for motor vehicle traffic.

Under lower-volume conditions on 6- and 8-lane arterials, the average extra time to make a right-turn and U-turn movement was up to 30–40 seconds longer for driveway volumes of 50 and 150 vehicles/hour, respectively (*6*).

On 4-lane arterials, a study in Florida (*7*) found that making a right turn followed by a U-turn at a downstream median opening was always slower than making a direct left turn (25 to 40 seconds slower on average, depending on the combination of arterial and driveway volumes). At the same time, the total control delay involved in making a right turn and a U-turn at a downstream median opening (i.e., considering only the waiting time to make the turns and ignoring the extra travel distance and time) was always less at any combination of volumes than making a direct left turn (*7*). This finding suggests that the right-turn and U-turn movements themselves were faster and less stressful than making a direct left turn. Making a U-turn at a traffic signal took an extra 40 to 65 seconds than making a U-turn at a median opening, depending on the combination of arterial and driveway volumes (*7*).

The delay to make a direct left turn will be higher when the median is not wide enough to store a vehicle (i.e., the entire left-turn maneuver must be made in one stage) (*1*). Under these conditions, the right-turn and U-turn movement will be faster at lower volumes than found in the Florida studies (*6*, *7*).

HCM6 methods (*8*) can be used to precisely compare delays and total travel times with and without a direct left turn at an access point, using traffic volumes, median storage width, lane configurations, and distance to the U-turn location as inputs. When traffic volumes (and corresponding driveway delays) are high, motorists will accept shorter (i.e., less safe) gaps than are suggested by the HCM6's default gap-acceptance values (*1*).

Motor Vehicle Safety

A motorist making a right turn followed by a U-turn experiences 30% fewer conflict points in making the maneuver, compared with a direct left turn (*2*). A study in Florida found 34% to 38% fewer actual conflicts (defined as a motorist having to brake, swerve, or noticeably decelerate) in situations with a right turn followed by a U-turn, compared with a direct left turn (*9*).

Median U-turn intersections, which operate in a similar manner as situations with a right turn followed by a U-turn, typically experience 20% to 50% fewer crashes relative to full-movement intersections (*3*). In Table 14-25 of the *Highway Safety Manual,* 1st ed. (HSM) a crash modification factor of 0.80 when replacing direct left turns with a right-turn and U-turn combination is reported (*10*).

Pedestrian and Bicycle Safety

No study was found that directly addressed pedestrian and bicycle safety when converting direct left turns to right-turn and U-turn movements. However, a study in New York City found that restricting left turns either part-time or full-time at intersections resulted in 41% fewer left-turn crashes involving pedestrian and bicycle injuries and 21% fewer overall crashes involving pedestrian and bicycle injuries (*11*). In New York City, left-turn crashes account for three times as many serious injuries and fatalities to pedestrians and bicyclists as do right-turn crashes (*11*).

Additional Information

- Chapters 2, 11, and 14 in this guide.
- *Access Management Manual,* Second ed.: Sections 17.3.3, 17.3.4, 20.2.8, and 20.5.6.

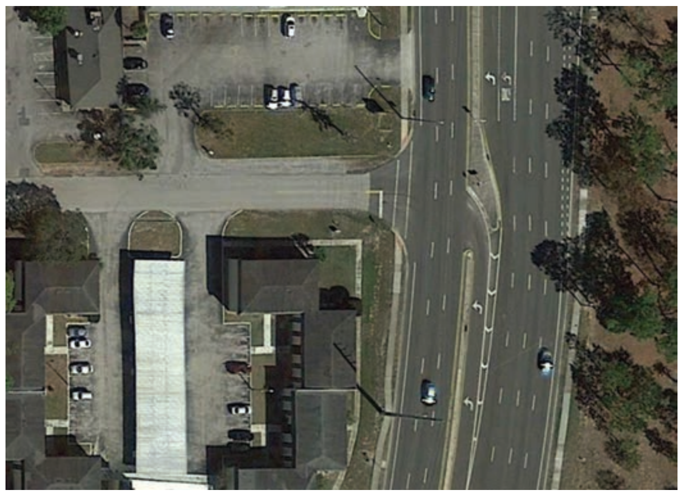
- *Access Management Application Guidelines*: Chapter 17, U-Turn Lane Requirements.
- *NCHRP Report 420*: Chapter 8, U-Turns as Alternatives to Direct Left Turns.

References

1. Gluck, J., H. S. Levinson, and V. Stover. *NCHRP Report 420: Impacts of Access Management Techniques.* Transportation Research Board, Washington, D.C., 1999.
2. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
3. Jagannathan, R. *Synthesis of the Median U-Turn Intersection Treatment, Safety, and Operational Benefits.* Publication FHWA-HRT-07-033, Federal Highway Administration, Washington, D.C., 2007.
4. Layton, R., G. Hodgson, and K. Hunter-Zaworski. Pedestrian and Bicyclist Impacts of Access Management. *Proceedings of the Third National Access Management Conference*, Fort Lauderdale, Fla., 1998.
5. Reid, J., L. Sutherland, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Median U-Turn Intersection Informational Guide.* Report FHWA-SA-14-069, Federal Highway Administration, Washington, D.C., Aug. 2014.
6. Lu, J., P. Liu, J. Fan, and J. Pernia. *Operational Evaluation of Right Turns Followed by U-Turns at Signalized Intersections (6 or More Lanes) as an Alternative to Direct Left Turns.* Florida Department of Transportation, Traffic Operations Office, Tallahassee, July 2004.
7. Lu, J., and P. Liu. *Operational Evaluation of Right Turns Followed by U-Turns (4-lane Arterials) as an Alternative to Direct Left Turns.* Florida Department of Transportation, Traffic Operations Office, Tallahassee, March 2005.
8. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
9. Lu, J., S. Dissanayake, N. Castillo, and K. Williams. *Safety Evaluation of Right Turns Followed by U-Turns as an Alternative to Direct Left Turns—Conflict Analysis.* Volume II. Florida Department of Transportation, Traffic Operations Office, Tallahassee, Aug. 2001.
10. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
11. Brunson, C., A. Getman, S. Hostetter, and R. Viola. Don't Cut Corners: Left Turn Pedestrian & Bicyclist Crash Study. Presented at 96th Annual Meeting of the Transportation Research Board, Washington, D.C., 2017.

CHAPTER 2

Non-Traversable Medians



Source: Photograph provided by Google Earth.

Description

Techniques in this group have the common element of installing a non-traversable median to manage access by restricting left-turn access to a limited number of locations. A non-traversable median is installed along an extended section of undivided highway, or a TWLTL lane is replaced with a non-traversable median. Non-traversable medians include raised curbs, slightly depressed medians (e.g., flush grass), and median barriers (*1*). See Chapters 1 and 11 for information about controlling left-turn access, egress, or both at specific driveways, which may include installing short sections of non-traversable median.

Tables 4 through 7 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

Exhibit 18-11 in the HCM6 gives the change in roadway free-flow speed resulting from a conversion from an undivided roadway or a nonrestrictive median to a restrictive (i.e., non-traversable) median (*3*). The change in free-flow speed (in mph) equals 1.5 p_{rm} – 3.7 p_{rm}, p_{curb}, where p_{rm} is the proportion of the link length (decimal) with a restrictive median and p_{curb} is the proportion of the link length (decimal) with a curb on the right side of the roadway.

Table 4. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships: Operations					Safety				
	🚗	🚶	🚲	🚌	🚚	🚗	🚶	🚲	🚌	🚚
Install non-traversable median along undivided highway.	↕ ●	↕ ●	↕ ●	↕ ●	↕ ●	↑ ●	↕ ●	↕ ◐	○	○
Convert TWLTL to non-traversable median.	↕ ●	↕ ●	↕ ●	↕ ●	↕ ●	↑ ●	↕ ●	↕ ◐	○	○
Install median barrier with no direct left-turn access or egress.	↕ ●	↕ ●	↕ ●	↕ ●	↕ ●	↑ ●	↕ ●	↕ ◐	○	○

Table 5. General trends associated with installing non-traversable medians.

Mode	Operations	Safety
🚗	Motor vehicle free-flow and travel speeds increase by up to 1.5 miles per hour (mph) (with no curb on the right side of the roadway) or decrease by up to 2.2 mph (with a curb on the right side), depending on the proportion of the roadway with a raised median (*2*, *3*). *See also* Chapters 5 and 9.	The motorized vehicle crash rate decreases (*4*–*6*). There is greatly reduced potential for head-on collisions (*7*). The number of vehicle–vehicle conflict points decreases.
🚶	Provides opportunities to develop two-stage pedestrian crossings that reduce pedestrian delay when crossing the street (*8*), except for barrier designs, which block pedestrian crossings (*9*). Pedestrian LOS goes down with increased motor vehicle speeds and up with decreased motor vehicle speeds (*3, 10*).	Decreases the number of vehicle–pedestrian conflict points and can provide a refuge in the middle of the roadway at pedestrian crossings, both of which improve pedestrian safety (*1*, *7*, *11*, *12*). Increases in vehicle speeds may negatively affect pedestrian safety and vice versa (*13*, *14*).
🚲	May reduce legal bicycle left-turn opportunities, although bicyclists may be able to dismount and cross as a pedestrian (*7*). Bicycle LOS goes down with increased motor vehicle speeds and up with decreased motor vehicle speeds (*3, 10*). Bicycle speeds similar to slightly higher than before (*15*).	Reduces vehicle–bicycle crash frequency at signalized intersections (*16*). Decreases the number of potential vehicle–bicycle conflict points (*7*). Increases in vehicle speeds may negatively affect bicycle safety and vice versa (*13*, *14*).
🚌	Similar effects as for motor vehicles. If necessary, bus left turns can be served with bus-only left-turn lanes (*7*). Can facilitate access to midblock bus stops if pedestrian crossing opportunities are provided, as bus passengers generally need to cross the roadway at some point during a round trip (*3*, *17*).	No documented effect beyond what is generally observed for motor vehicle traffic (for buses) and pedestrians (for boarding and alighting passengers).
🚚	Truck speeds increase, as long as traffic volumes do not increase by more than 285 vehicles per hour per lane as a result of changes in traffic patterns (*15*). Truck LOS goes up with increased speeds and down with decreased speeds (*18*).	No documented effect beyond that generally observed for motor vehicle traffic.

Table 6. Crash rates following the installation of non-traversable medians.

		Percent Change in Crash Rate	
Before Condition	Number of Studies	Range of Results	Average (Median) Result
Undivided	10	−2 to −67	−35
TWLTL	16	+15 to −57	−27

The magnitude of the corresponding change in average running speed will be slightly lower, as discussed in the appendix.

When a non-traversable median is installed on an undivided roadway or a roadway with a TWLTL, through traffic will experience less delay than before, due to the reduction in the number of locations where left turns can be made (*3*). See Chapter 1 for details.

When a non-traversable median is installed on an undivided roadway and left-turn lanes are provided at median openings, through traffic will experience less delay than before, because vehicles stopped to make a left turn will no longer block through vehicles (*3*). See Chapter 9 for more information.

If no median openings are provided between signalized intersections or if U-turns are prohibited at median openings, delay may increase at the signalized intersections as a result of the increased U-turning volume (*5*). Chapter 19 in the HCM6 (*3*) can be used to estimate the change in delay resulting from the additional U-turns. Alternative intersection designs such as the Michigan U-turn or restricted crossing U-Turn address this issue by relocating U-turns from the main signalized intersection to adjacent secondary intersections. These intersection forms can be analyzed by using the methods in Chapter 23 in the HCM6 (*3*). See Chapter 12 for more information.

Motor Vehicle Safety

NCHRP Report 420 (*5*) summarized the results of a number of studies between 1983 and 1995 that investigated the change in crash rates following the installation of non-traversable medians (6), as shown in Table 6.

A 2012 study of 18 Florida locations where TWLTLs had been converted to non-traversable medians found an average 30% reduction in the crash rate following the installation of the non-traversable median (*6*). The crash-rate reduction was much greater on 6-lane arterials (−37%) than on 4-lane arterials (−5%).

Tables 13-10 and 13-11 in the HSM provide the following crash modification factors related to installing a median on urban and rural roadways (*4*):

- Urban 2-lane roadways: 0.61
- Urban multi-lane arterials: 0.78 (injury crashes), 1.09 (non-injury crashes)
- Rural multi-lane arterials: 0.88 (injury crashes), 0.82 (non-injury crashes)

Bowman et al. (*19*) developed a set of predictive models that collectively addressed vehicle–vehicle crashes for three cross-section types (i.e., raised-curb median, TWLTL, and undivided). The appendix provides additional detail about these models.

Pedestrian Operations

Equations 18-32 and 18-35 in the HCM6 (*3*) are used to determine the effect of motorized vehicle speeds on pedestrian LOS. An increase in average traffic speed of 2 mph worsens the pedestrian LOS score by 0.03 points (at 20 mph) to 0.08 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter.

Installing a non-traversable median may improve pedestrian LOS in one of two ways: (*a*) by potentially providing an opportunity to develop legal midblock pedestrian crossings where none existed before or (*b*) by reducing pedestrian delay at an existing legal crossing by facilitating two-stage pedestrian crossings (*3*). The impact on the pedestrian LOS score depends on how much time the pedestrian saves and the quality of the pedestrian environment along the roadway ("link") and at signalized intersections. Greater time-savings and poorer link and intersection pedestrian environments result in greater improvements in the pedestrian LOS score. Providing a midblock pedestrian crossing can potentially improve the pedestrian LOS score by 1 to 2 points, while converting a one-stage crossing to a two-stage crossing typically improves the pedestrian LOS score by 0.1 to 0.8 points.

Pedestrian Safety

Table 7 summarizes the results of studies that have evaluated the effect of non-traversable medians on vehicle–pedestrian crash rates.

Bowman et al. (*19*) developed a set of predictive models that collectively addressed three cross-section types (i.e., raised-curb median, TWLTL, and undivided). The dependent variable (i.e., crash rate) was expressed in terms of vehicle–pedestrian crashes per 100 million vehicle miles. The model indicates that vehicle–pedestrian crash rate is lowest for the raised-curb median, regardless of area type or land use. The appendix provides additional detail about these models.

Zegeer et al. (*20*) developed a crash prediction model that predicts the frequency of vehicle–pedestrian crashes at unsignalized crossing locations. The model includes an input variable that is used to indicate whether a raised-curb median is present (as a refuge) for part of the crossing. The model indicates that vehicle–pedestrian crash frequency decreases when a raised-curb median is present.

Bicycle Operations

Equations 18-41 and 18-44 in the HCM6 (*3*) are used to determine the effect of motorized vehicle speeds on bicycle LOS. An increase in average traffic speed of 2 mph worsens the bicycle LOS score by 0.57 points (at 21 mph or less), 0.17 points (at 25 mph), 0.05 points (at 40 mph), and 0.03 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter.

Table 7. Studies that have evaluated the effect of non-traversable medians on vehicle–pedestrian crash rates.

		Average Percent Change in Crash Rate by Previous Median Type	
Source	**Crash Type**	**Undivided**	**TWLTL**
Bowman and Vecellio (*12*)	Midblock	−42	−42
	intersection	−58	−61
	Central business location	—	−54
	Suburban location	—	−51
Parsonson et al. (*11*)	Fatal	—	−78
Alluri et al. (*6*)	All	—	−29[a]

Note: A dash indicates that the combination of median type and crash type was not studied.
[a]Not statistically significant.

A simulation study (*15*) found that converting a TWLTL to a raised median reduced bicycle speeds by 0.04 mph if no change in traffic volume resulted from the conversion. However, this speed reduction would be offset if traffic volumes increased as a result of the conversion. With a raised median, bicycle speeds increased by 0.23 mph for each increase of 100 vehicles per hour per lane. Higher through traffic volumes seemed to reduce opportunities for driveway traffic to turn onto the roadway, which decreased the chance that driveway traffic would interfere with bicycle traffic. The break-even point for bicycle speed occurred at an increase of about 20 vehicles per hour per lane.

Bicycle Safety

Miranda-Moreno et al. (*16*) developed two models indicating that the vehicle–bicycle crash rate at signalized intersections decreases when a raised median is present; however, this relationship was not statistically significant in either model.

Alluri et al. (*6*) studied the effect of converting TWLTLs to raised medians in Florida. With respect to vehicle–bicycle crashes, the study found a 4.5% reduction in the crash rate that was not statistically significant.

Bus Operations

The information in HCM6 Chapter 18 (*3*) can be used to estimate the change in average bus speeds resulting from improvements in midblock running speed. This estimation in turn can be used to estimate the change in bus LOS for the segment. At 30-minute bus headways and with seated loads and reliable service, a 1-mph increase in average bus speed produces a 0.08–0.12 improvement in the bus LOS score, with 0.75 points representing the range covered by one LOS letter (*3*, *17*).

Truck Operations

Section P in Exhibit 3 of *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual* (*21*), which is derived from *NCFRP Report 31: Incorporating Truck Analysis into the* Highway Capacity Manual (*18*), can be used to estimate the effect of improved truck free-flow and travel speeds on overall truck LOS. On a level street with a 35-mph free-flow speed, increasing average truck speeds from 25 to 26 mph results in a 1.3 percentage point increase in the truck LOS index, while increasing average truck speeds from 17.5 to 18.5 mph results in a 7.0 percentage point increase, with 10 percentage points representing the range covered by one LOS letter.

A simulation study (*15*) found that converting a TWLTL to a raised median improved truck speeds by 2.1 mph if no change in traffic volume occurred as a result of the conversion. However, this speed increase would be partially offset if traffic volumes increased as a result of the conversion. With a raised median, truck speeds decreased by 0.72 mph for each increase of 100 vehicles per hour per lane. The break-even point for truck speed occurred at an increase of about 280 vehicles per hour per lane.

Additional Information

- Chapters 1, 3, 5, 7, 11, and 12 in this guide.
- *Access Management Manual,* Second ed.: Chapter 17, Medians and Two-Way Left-Turn Lanes, Section 20.2.7
- *Access Management Application Guidelines*: Chapter 15, Median Applications and Design.
- *NCHRP Report 420*: Chapter 6, Median Alternatives.

References

1. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
2. Texas Transportation Institute; Kittelson & Associates, Inc.; and Purdue University. *Predicting the Performance of Automobile Traffic on Urban Streets.* Final report, NCHRP Project 03-79. Transportation Research Board of the National Academies, Washington, D.C., Jan. 2008.
3. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
4. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
5. Gluck, J., H. S. Levinson, and V. Stover. *NCHRP Report 420: Impacts of Access Management Techniques.* Transportation Research Board, Washington, D.C., 1999.
6. Alluri, P., A. Gan, K. Haleem, S. Miranda, E. Echezabal, A. Diaz, and S. Ding. *Before and After Safety Study of Roadways Where New Medians Have Been Added.* Lehman Center for Transportation Research, Florida International University, Miami, Dec. 2012.
7. Dixon, K. K., R. D. Layton, M. Butorac, P. Ryus, J. L. Gattis, L. Brown, and D. Huntington. *Access Management Application Guidelines.* Transportation Research Board, Washington, D.C., 2016.
8. Redmon, T. *Safety Benefits of Raised Medians and Pedestrian Refuge Areas.* Publication FHWA-SA-10-020. Federal Highway Administration, Washington, D.C., 2010.
9. New Jersey Department of Transportation and Pennsylvania Department of Transportation. *Smart Transportation Guidebook.* Trenton, N.J., and Harrisburg, Pa., March 2008.
10. Dowling, R., D. Reinke, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, N. Rouphail, and J. Bonneson. *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
11. Parsonson, P. S., M. G. Waters III, and J. S. Fincher. Georgia Study Confirms the Continuing Safety of Raised Medians Over Two-Way Left-Turn Lanes. Fourth National Conference on Access Management, Portland, Ore., Aug. 2000.
12. Bowman, B. L., and R. L. Vecellio. Effect of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1445, 1994, pp. 169–179.
13. Chandler, B. E., M. C. Myers, J. E. Atkinson, T. E. Bryer, R. Retting, J. Smithline, J. Trim, P. Wojtkiewicz, G. B. Thomas, S. P. Venglar, S. Sunkari, B. J. Malone, and P. Izadpanah. *Signalized Intersections Informational Guide,* 2nd ed. Publication No. FHWA-SA-13-027. Federal Highway Administration, Washington, D.C., July 2013.
14. National Association of City Transportation Officials. *Urban Street Design Guide.* National Association of City Transportation Officials, Washington, D.C., Oct. 2013.
15. Butorac, M., J. Bonneson, K. Connolly, P. Ryus, B. Schroeder, K. Williams, Z. Wang, S. Ozkul, and J. Gluck. *Web-Only Document 256: Assessing Interactions Between Access Management Treatments and Multimodal Users.* Transportation Research Board, Washington, D.C., 2018.
16. Miranda-Moreno, L. F., J. Strauss, and P. Morency. Disaggregate Exposure Measures and Injury Frequency Models of Cyclist Safety at Signalized Intersections. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2236, 2011, pp. 74–82.
17. Kittelson & Associates, Inc.; Parsons Brinckerhoff; KFH Group, Inc.; Texas A&M Transportation Institute; and Arup. *TCRP Report 165: Transit Capacity and Quality of Service Manual,* 3rd ed. Transportation Research Board of the National Academies, Washington, D.C., 2013.
18. Dowling, R., G. List, B. Yang, E. Witzke, and A. Flannery. *NCFRP Report 31: Incorporating Truck Analysis into the Highway Capacity Manual.* Transportation Research Board of the National Academies, Washington, D.C., 2014.
19. Bowman, B., R. Vecellio, and J. Miao. Vehicle and Pedestrian Accident Models for Median Locations. *Journal of Transportation Engineering,* Vol. 121, No. 6, American Society of Civil Engineers, Washington, D.C., Nov.–Dec. 1994, pp. 531–537.
20. Zegeer, C. V., J. R. Stewart, H. H. Huang, P. A. Lagerwey, J. Feaganes, and B. J. Campbell. *Safety Effects of Marked Versus Unmarked Crosswalks at Uncontrolled Locations: Final Report and Recommended Guidelines.* Report FHWA-HRT-04-100. Federal Highway Administration, Washington, D.C., Aug. 2005.
21. Dowling, R., P. Ryus, B. Schroeder, M. Kyte, T. Creasey, N. Rouphail, A. Hajbabaie, and D. Rhoades. *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual.* Transportation Research Board, Washington, D.C., 2016.

CHAPTER 3

Continuous Two-Way Left-Turn Lanes

Source: Photograph provided by the authors.

Description

A *TWLTL* provides a location in the center of the roadway for storing vehicles from either direction that are waiting to make a left turn. TWLTLs can be developed along undivided roadways by widening the roadway or by reducing the number of through lanes (i.e., a road diet).

Tables 8 through 10 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

Exhibit 18-13 in the HCM6 gives average through vehicle delay in terms of seconds per vehicle per full, unsignalized access point (*2*).

Delay values in this table assume 10% of the traffic on the street turns right at the access point and 10% turns left. Adjust the delay values proportionately for other turning percentages. Reduce the delay values by 50% if one turning movement is provided with an appropriately dimensioned turn lane or the turning movement does not exist. There is no delay if both turning movements are provided with turn lanes (or if one movement has a turn lane and the other movement does not exist). See Chapter 9 for additional information specific to left-turn lanes.

Table 8. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships: Operations					Safety				
										
Install continuous TWLTL.	↑ ●	↓ ●	↓ ●	↕ ●	↑ ●	↕ ●	↓ ●	↓ ◐	○	○

Note: Trends are relative to a *before* condition of an undivided roadway.

Table 9. General trends associated with installing continuous TWLTLs.

Mode	Operations	Safety
	Motor vehicle free-flow and travel speeds increase by up to a few mph, depending on traffic volumes, the number of access points, and the proportion of the roadway with a TWLTL (*1*, *2*).	The motor vehicle crash rate decreases, but by a smaller amount compared with installing a non-traversable median (*3*). Creates the potential for overlapping left-turn movements (*4*).
	Increased pedestrian delay and decreased pedestrian LOS at midblock pedestrian crossings where the crossing distance is increased as a result of the TWLTL. Small negative effect on pedestrian LOS due to increased motor vehicle speeds (*2, 5*).	Increased pedestrian exposure when the crossing distance is increased as a result of the TWLTL; the TWLTL does not provide a pedestrian refuge (*4*). Similar vehicle–pedestrian crash rates as undivided highways (*6*). Increases in vehicle speeds may negatively affect pedestrian safety (*7, 8*).
	Negative effect on bicycle LOS due to increased motor vehicle speeds (*2, 5*).	Increases in vehicle speeds may negatively affect bicycle safety (*7, 8*).
	Similar effects as for motor vehicles. May make access to midblock bus stops more difficult, as bus passengers generally need to cross the roadway at some point during a round trip (*9*, *10*).	No documented effect beyond that generally observed for motor vehicle traffic (for buses) and pedestrians (for boarding and alighting passengers).
	Improved truck LOS due to improved speeds (*11*).	No documented effect beyond that generally observed for motor vehicle traffic.

Note: Trends are relative to a *before* condition of an undivided roadway.

Table 10. Average through vehicle delay per full, unsignalized access point.

Midsegment Volume (vehicles per hour per lane)	Through Vehicle Delay (seconds per vehicle per access point) by Number of Through Lanes: 1 Lane	2 Lanes	3 Lanes
200	0.04	0.04	0.05
300	0.08	0.08	0.09
400	0.12	0.15	0.15
500	0.18	0.25	0.15
600	0.27	0.41	0.15
700	0.39	0.72	0.15

Motor Vehicle Safety

NCHRP Report 420 (*3*) summarized the results of 12 studies between 1974 and 1994 that investigated the change in crash rates following the installation of TWLTLs. The average (median) change in crash rate was –38%, with greater improvements seen in rural areas (–53%) than in urban and suburban areas (–23%).

Table 13-6 in the HSM provides a crash modification factor of 0.71 for the situation where a 4-lane undivided urban arterial is converted into two through lanes plus a TWLTL (*12*):

- Urban 2-lane roadways: 0.61
- Urban multi-lane arterials: 0.78 (injury crashes), 1.09 (non-injury crashes)
- Rural multi-lane arterials: 0.88 (injury crashes), 0.82 (non-injury crashes)

Bowman et al. (*13*) developed a set of predictive models that collectively addressed vehicle–vehicle crashes for three cross-section types (i.e., raised-curb median, TWLTL, and undivided). The appendix provides additional detail about these models.

Pedestrian Operations

Equations 18-32 and 18-35 in the HCM6 (*2*) are used to determine the effect of motorized vehicle speeds on pedestrian LOS. An increase in average traffic speed of 2 mph worsens the pedestrian LOS score by 0.03 points (at 20 mph) to 0.08 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter.

Installing a TWLTL may decrease pedestrian LOS when (*a*) the crossing distance is widened and (*b*) it is nevertheless faster to cross the street at legal midblock locations than to detour to the nearest signalized intersection to cross. The impact on the pedestrian LOS score depends on the extra delay experienced by pedestrians and the quality of the pedestrian environment along the roadway (“link”) and at signalized intersections. Higher delays and better link and intersection pedestrian environments result in greater decreases in the pedestrian LOS score. With a midrange pedestrian environment, the extra delay typically results in a reduction in the pedestrian LOS score of 0.2 to 0.9 points.

Pedestrian Safety

A study by Bowman and Vecellio (*6*) found that undivided roadways and roadways with TWLTLs had similar vehicle–pedestrian crash rates (midblock: 6.69 crashes per 100 million vehicle miles—undivided, 6.66—TWLTL *and* intersection: 2.32 crashes per 100 million entering vehicles—undivided, 2.49—TWLTL). The vehicle–pedestrian crash models developed by Bowman et al. (*13*) can be used to estimate crash rates on roadways with TWLTLs, as well as on undivided roadways and roadways with raised medians. The appendix provides additional detail about these models.

Bicycle Operations

Equations 18-41 and 18-44 in the HCM6 (*2*) are used to determine the effect of motorized vehicle speeds on bicycle LOS. An increase in average traffic speed of 2 mph worsens the bicycle LOS score by 0.57 points (at 21 mph or less), 0.17 points (at 25 mph), 0.05 points (at 40 mph), and 0.03 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter.

Bus Operations

Chapter 18 in the HCM6 (*2*) can be used to estimate the change in average bus speeds resulting from improvements in midblock running speed. This estimation in turn can be used to estimate the change in bus LOS for the segment. At 30-minute bus headways and with seated loads and reliable service, a 1-mph increase in average bus speed produces a 0.08–0.12 improvement in the bus LOS score, with 0.75 points representing the range covered by one LOS letter (*2*, *10*).

Truck Operations

Section P in Exhibit 3 of *NCHRP Report 825* (*14*), which is derived from *NCFRP Report 31* (*11*), can be used to estimate the effect of improved truck free-flow and travel speeds on overall truck LOS. On a level street with a 35-mph free-flow speed, increasing average truck speeds from 25 to 26 mph results in a 1.3 percentage point increase in the truck LOS index, while increasing average truck speeds from 17.5 to 18.5 mph results in a 7.0 percentage point increase, with 10 percentage points representing the range covered by one LOS letter.

Additional Information

- Chapters 2 and 9 in this guide.
- *Access Management Manual,* Second ed.: Chapter 17, Medians and Two-Way Left-Turn Lanes, Section 20.3.3.
- *Access Management Application Guidelines*: Chapter 15, Median Applications and Design.
- *NCHRP Report 420*: Chapter 6, Median Alternatives.

References

1. Texas Transportation Institute; Kittelson & Associates, Inc.; and Purdue University. *Predicting the Performance of Automobile Traffic on Urban Streets.* Final report, NCHRP Project 03-79. Transportation Research Board of the National Academies, Washington, D.C., Jan. 2008.
2. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
3. Gluck, J., H. S. Levinson, and V. Stover. *NCHRP Report 420: Impacts of Access Management Techniques.* Transportation Research Board, Washington, D.C., 1999.
4. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
5. Dowling, R., D. Reinke, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, N. Rouphail, and J. Bonneson. *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
6. Bowman, B. L., and R. L. Vecellio. Effect of Urban and Suburban Median Types on Both Vehicular and Pedestrian Safety. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1445, 1994, pp. 169–179.
7. Chandler, B. E., M. C. Myers, J. E. Atkinson, T. E. Bryer, R. Retting, J. Smithline, J. Trim, P. Wojtkiewicz, G. B. Thomas, S. P. Venglar, S. Sunkari, B. J. Malone, and P. Izadpanah. *Signalized Intersections Informational Guide,* 2nd ed. Publication No. FHWA-SA-13-027. Federal Highway Administration, Washington, D.C., July 2013.
8. National Association of City Transportation Officials. *Urban Street Design Guide.* National Association of City Transportation Officials, Washington, D.C., Oct. 2013.
9. Redmon, T. *Safety Benefits of Raised Medians and Pedestrian Refuge Areas.* Publication FHWA-SA-10-020. Federal Highway Administration, Washington, D.C., 2010.
10. Kittelson & Associates, Inc.; Parsons Brinckerhoff; KFH Group, Inc.; Texas A&M Transportation Institute; and Arup. *TCRP Report 165: Transit Capacity and Quality of Service Manual,* 3rd ed. Transportation Research Board of the National Academies, Washington, D.C., 2013.

11. Dowling, R., G. List, B. Yang, E. Witzke, and A. Flannery. *NCFRP Report 31: Incorporating Truck Analysis into the Highway Capacity Manual.* Transportation Research Board of the National Academies, Washington, D.C., 2014.
12. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
13. Bowman, B., R. Vecellio, and J. Miao. Vehicle and Pedestrian Accident Models for Median Locations. *Journal of Transportation Engineering,* Vol. 121, No. 6, American Society of Civil Engineers, Washington, D.C., Nov.–Dec. 1994, pp. 531–537.
14. Dowling, R., P. Ryus, B. Schroeder, M. Kyte, T. Creasey, N. Rouphail, A. Hajbabaie, and D. Rhoades. *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the* Highway Capacity Manual. Transportation Research Board, Washington, D.C., 2016.

CHAPTER 4

Frontage and Service Roads

Source: Photograph provided by the authors.

Description

A *service road* is a local roadway parallel to an arterial roadway whose function is to provide direct access to properties adjacent to the arterial; it may be located in front of or in back of properties, relative to the arterial. A *frontage road* is a type of service road located between the arterial and the adjacent property (*1*). Access to the service road may occur at intersections with crossroads that intersect the arterial or, in the case of some one-way frontage roads, via slip ramps between the arterial and frontage road.

Tables 11 through 13 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

Chapter 18 in the HCM6 (*3*) provides methods for estimating the change in arterial travel speed between traffic signals resulting from shifting property access from an arterial to a service road. In a first method, HCM6 Equation 18-3 and Exhibit 18-11 give the reduction in free-flow speed due to access point density (*3*). This reduction (in mph) equals $-0.078\ D_a/N_{th}$, where D_a is the number of access points per mile (considering both sides of the roadway) and N_{th} is the number of through lanes in the direction of travel. The resulting increase in average travel speed will be slightly lower, as discussed in the appendix.

Table 11. Multimodal operations and safety performance summary.

	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
Access Management Technique										
Install frontage road to provide access to individual parcels.	↕ ●	↕ ●	↕ ●	↓ ◐	↑ ●	↑ ●	↕ ◐	↕ ◐	○	○
Increase distance from service road to arterial along crossroad.	↑ ●	↓ ●	↓ ◐	○	○	↑ ◐	↑ ◐	↑ ◐	○	○
Construct service road behind properties abutting the arterial.	↕ ●	↔ ●	↔ ●	↕ ◐	○	↑ ◐	↑ ◐	↑ ◐	○	○
Construct bypass road to remove through traffic from arterial.	↑ ●	↑ ●	↑ ●	↑ ◐	↑ ●	↑ ◐	↑ ◐	↑ ◐	○	○

Note: ↔ = unchanged performance.

Table 12. General trends associated with developing frontage and service roads.

Mode	Operations	Safety
	Motor vehicle free flow and travel speeds increase by up to a few miles per hour between intersections. Where service roads are accessed from crossroads that intersect the arterial at traffic signals, delay to the arterial roadway may increase due to the increased turning movement volumes at the signalized intersection (*2*, *3*). Service road–crossroad intersections located too close to crossroad–arterial intersections may be blocked by queued traffic (*4*). Signalized service road–crossroad intersections located close to crossroad–arterial intersections create signal timing challenges (*4*).	The motorized vehicle crash rate on the arterial roadway decreases (*4*, *5*). Turning movements to and from properties occur in a lower-volume, lower-speed environment rather than on the arterial, thereby improving safety (*4*). Better separation of conflict points when service road–crossroad intersections are located farther away from crossroad–arterial intersections (*4*). Reduced conflict points when access is shifted to a service road behind properties abutting the arterial.
	All other factors being equal, pedestrian LOS will be better on a service road than along the arterial, due to lower traffic volumes and potentially lower speeds (*3*). Pedestrian travel times may increase due to less-direct routes (e.g., bowing of frontage roads away from the arterial at crossroads), greater delay at unsignalized crossroad–frontage road intersections as opposed to using a signalized arterial–crossroad intersection, or needing two traffic signal cycles to fully cross the widened arterial (where frontage roads are immediately adjacent to the main roadway).	Better separation of conflict points when service road–crossroad intersections are located farther away from crossroad–arterial intersections (*4*). Reduced conflict points when access is shifted to a service road behind properties abutting the arterial. Unsignalized service road–crossroad intersections may be more challenging to cross than signalized arterial–crossroad intersections.
	When bicycle traffic is relocated from the arterial to a service road, bicycle LOS between intersections will improve due to the lower traffic volumes, typically lower heavy vehicle percentages, and potentially lower traffic speeds (*3, 6*). However, bicycle travel times may increase due to less direct routings and delay at unsignalized crossroad–service road intersections. One-way service roads may force out-of-direction bicycle travel to access land uses on the opposite side of the arterial.	Reduced vehicle speeds along service roads, relative to the arterial, may positively affect bicycle safety (*8*, *9*). Better separation of conflict points when service road–crossroad intersections are located farther away from crossroad–arterial intersections (*4*). Reduced conflict points when access is shifted to a service road behind properties abutting the arterial. Unsignalized service road–crossroad intersections may be more challenging to cross than signalized arterial–crossroad intersections.

Table 12. (Continued).

Mode	Operations	Safety
	Buses remaining on an arterial where frontage roads are installed will have reduced flexibility for locating bus stops (particularly to serve midblock trip generators). Buses diverting to a service road will experience lower travel speeds, which lowers bus LOS (*3, 6*).	No documented effect beyond that generally observed for motor vehicle traffic.
	Similar to motor vehicles on the arterial, but with greater benefit for trucks, as they accelerate more slowly to their running speed after stopping or slowing (*9*). Improved truck LOS due to improved speeds (*10*).	No documented effect beyond that generally observed for motor vehicle traffic.

In a second method, Exhibit 18-13 gives the average through vehicle delay in terms of seconds per vehicle per full, unsignalized access point (*3*), as shown in Table 13.

Delay values in this table assume 10% of the traffic on the street turns right at the access point and 10% turns left. Adjust the delay values proportionately for other turning percentages. Reduce the delay values by 50% if one turning movement is provided with an appropriately dimensioned turn lane or a turning movement does not exist. There is no delay if both turning movements are provided with turn lanes (or if one movement has a turn lane and the other movement does not exist). See Chapter 9 for additional information specific to turn lanes.

Chapter 19 in the HCM6 can be used to determine the change in delay at signalized intersections along the arterial resulting from increased turning movement volumes, as well as delay at signalized crossroad–service road intersections (*8*). Chapters 20 to 22 in the HCM6, which address different types of unsignalized intersections, can be used to evaluate the operation of unsignalized crossroad–service road intersections (*3*).

Chapters 19 and 20 can be used to determine the 95th-percentile queue length on crossroads at arterial–crossroad intersections (*3*). This distance is a factor in determining the minimum separation between arterial–crossroad and arterial–service road intersections.

Motor Vehicle Safety

Frontage and service roads segregate through local access traffic and thereby reduce the frequency and severity of conflicts on the arterial road (*4*). Because conflict points are relocated from the main roadway to the service road, there may not be any change in the total number of conflict points (depending on the turning movements allowed at each driveway before and after

Table 13. Average through vehicle delay.

Midsegment Volume (vehicles per hour per lane)	Through Vehicle Delay (seconds per vehicle per full, unsignalized access point) by Number of Through Lanes		
	1 Lane	2 Lanes	3 Lanes
200	0.04	0.04	0.05
300	0.08	0.08	0.09
400	0.12	0.15	0.15
500	0.18	0.25	0.15
600	0.27	0.41	0.15
700	0.39	0.72	0.15

the development of service roads). However, because service roads are lower-volume environments and (frequently) lower-speed environments, the number and severity of crashes would be expected to be lower, relative to the situation without service roads.

Drawing from a review of a number of crash studies, *NCHRP Report 420* (*4*) indicated that each additional access point per mile increases a roadway's crash rate by 4%, relative to the crash rate experienced at 10 access points per mile (total of both sides). Thus, a road with 60 access points per mile would be expected to have 200% more (i.e., three times as many) crashes as a road with 10 access points per mile.

The HSM provides the following crash modification factors related to urban and suburban arterials in Table 13-58 (*5*):

- Reducing driveways from 48 to 26–48 per mile: 0.71
- Reducing driveways from 26–48 to 10–24 per mile: 0.69
- Reducing driveways from 10–24 to less than 10 per mile: 0.75

Pedestrian Operations

Equations 18-32 and 18-35 in the HCM6 (*3*) can determine the effect of motorized vehicle speeds on pedestrian link LOS. An increase in average traffic speed of 2 mph worsens the pedestrian link LOS score by 0.03 points (at 20 mph) to 0.08 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter. Unsignalized access spacing was not found to be a significant predictor of ratings of pedestrian LOS (*6*).

Chapter 19 in the HCM6 can be used to determine the changes in pedestrian crossing delay and pedestrian intersection LOS at signalized intersections that result from the development of frontage roads. Chapter 20 in the HCM6 can be used to estimate pedestrian delay at two-way stop-controlled service road–crossroad intersections (*3*).

Bicycle Operations

Equations 18-41 and 18-44 (*3*) are used to determine the effect of motorized vehicle speeds on bicycle LOS. An increase in average traffic speed of 2 mph worsens the bicycle LOS score by 0.57 points (at 21 mph or less), 0.17 points (at 25 mph), 0.05 points (at 40 mph), and 0.03 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter.

Equations 18-46 and 18-47 (*3*) can determine the effect of unsignalized access spacing on bicycle LOS. There is no effect when the access density (total of both sides) is 20 access points per mile or less. Decreasing the access point density by 10 points per mile (e.g., from 30 to 20 points per mile) improves bicycle LOS by 0.14 points while decreasing the access point density by 20 points per mile improves bicycle LOS by 0.28 points. These results assume that heavy vehicles make up 5% of the traffic volume and that roadway links and signalized intersections are weighted the same when calculating overall bicycle LOS.

Chapter 19 in the HCM6 (*3*) can be used to determine the changes in bicycle delay and bicycle intersection LOS at signalized intersections that result from the development of frontage roads.

Bus Operations

Chapter 18 in the HCM6 (*3*) can be used to estimate the change in average bus speeds resulting from reduced traffic volumes, changes in routing, or both. This information in turn can be used to estimate the change in bus LOS for the segment. At 30-minute bus headways with seated loads and reliable service, a 1-mph increase in average bus speed produces a

0.08–0.12 improvement in the bus LOS score, with 0.75 points representing the range covered by one LOS letter (*3*, *10*).

Truck Operations

Section P in Exhibit 3 of *NCHRP Report 825* (*11*), derived from *NCFRP Report 31* (*12*), can be used to estimate the effect of improved truck free-flow and travel speeds on overall truck LOS. On a level street with a 35-mph free-flow speed, increasing average truck speeds from 25 to 26 mph results in a 1.3 percentage point increase in the truck LOS index, while increasing average truck speeds from 17.5 to 18.5 mph results in a 7.0 percentage point increase, with 10 percentage points representing the range covered by one LOS letter.

Additional Information

- Chapter 12 in this guide.
- *Access Management Manual,* Second ed.: Sections 20.4.10 and 20.4.11.
- *Access Management Application Guidelines*: Section 19.3.1.
- *NCHRP Report 420*: Chapter 10, Frontage Roads.

References

1. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
2. Texas Transportation Institute; Kittelson & Associates, Inc.; and Purdue University. *Predicting the Performance of Automobile Traffic on Urban Streets.* Final report, NCHRP Project 03-79. Transportation Research Board of the National Academies, Washington, D.C., Jan. 2008.
3. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
4. Gluck, J., H. S. Levinson, and V. Stover. *NCHRP Report 420: Impacts of Access Management Techniques.* Transportation Research Board, Washington, D.C., 1999.
5. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
6. Dowling, R., D. Reinke, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, N. Rouphail, and J. Bonneson. *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
7. Chandler, B. E., M. C. Myers, J. E. Atkinson, T. E. Bryer, R. Retting, J. Smithline, J. Trim, P. Wojtkiewicz, G. B. Thomas, S. P. Venglar, S. Sunkari, B. J. Malone, and P. Izadpanah. *Signalized Intersections Informational Guide,* 2nd ed. Publication No. FHWA-SA-13-027. Federal Highway Administration, Washington, D.C., July 2013.
8. National Association of City Transportation Officials. *Urban Street Design Guide.* National Association of City Transportation Officials, Washington, D.C., Oct. 2013.
9. Harwood, D. W., D. J. Torbic, K. R. Richard, W. D. Glauz, and L. Elefteriadou. *NCHRP Report 505: Review of Truck Characteristics as Factors in Roadway Design.* Transportation Research Board of the National Academies, Washington, D.C., 2003.
10. Kittelson & Associates, Inc.; Parsons Brinckerhoff; KFH Group, Inc.; Texas A&M Transportation Institute; and Arup. *TCRP Report 165: Transit Capacity and Quality of Service Manual,* 3rd ed. Transportation Research Board of the National Academies, Washington, D.C., 2013.
11. Dowling, R., P. Ryus, B. Schroeder, M. Kyte, T. Creasey, N. Rouphail, A. Hajbabaie, and D. Rhoades. *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual.* Transportation Research Board, Washington, D.C., 2016.
12. Dowling, R., G. List, B. Yang, E. Witzke, and A. Flannery. *NCFRP Report 31: Incorporating Truck Analysis into the* Highway Capacity Manual. Transportation Research Board of the National Academies, Washington, D.C., 2014.

CHAPTER 5

Unsignalized Median Openings

Source: Photograph provided by Google Earth.

Description

Techniques in this group involve configuring the design of unsignalized median openings, including providing left-turn channelization, adjusting the median width, and installing left-turn acceleration lanes. These techniques can be considered wherever a non-traversable median exists to improve roadway operations and safety where openings in the median are provided. See Chapter 2 for information relating to medians in general.

Tables 14 through 16 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

Methods in Chapter 20 in the HCM6 (*2*) can be used to compare intersection operations with and without two-stage minor street left-turn operation. The operation of an intersection providing steady flow in one direction can be evaluated using the HCM6 by setting the through volume for the steady-flow direction to zero.

Motor Vehicle Safety

The HSM (*4*) provides the following crash modification factors (CMFs) for multiple-vehicle crashes related to widening the intersection median width in 3-feet increments:

- Rural, four-leg unsignalized: 0.96 (all severities), 0.96 (injury)
- Urban and suburban, four-leg unsignalized: 1.06 (all severities), 1.05 (injury)

Table 14. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships: Operations [car]	Operations [pedestrian]	Operations [bicycle]	Operations [bus]	Operations [truck]	Safety [car]	Safety [pedestrian]	Safety [bicycle]	Safety [bus]	Safety [truck]
Increase median width to store left turn egress vehicles.	↑ ●	↑ ●	↔ ◐	○	○	↕ ●	↑ ●	○	○	○
Channelize median to control merge of left turn egress vehicles.	○	○	○	○	○	↑ ◐	○	○	○	○
Develop left turn acceleration lane.	↑ ◐	○	↔ ◐	○	○	↕ ◐	○	○	↕ ◐	↕ ◐
Provide full access with steady flow in one direction of arterial.	↑ ●	↓ ◐	↓ ◐	○	○	○	↓ ◐	↓ ◐	○	○
Channelize left turns to keep vehicles from returning to through lanes.	○	○	○	○	○	↕ ●	○	○	○	○
Channelize left turns across wide medians to improve offset.	○	↑ ●	↔ ◐	○	○	↑ ●	↑ ◐	○	○	○
Increase effective approach width of right-angle median crossovers.	○	○	○	○	○	○	○	○	○	○

Note: ↔ = unchanged performance.

Table 15. General trends associated with improvements to unsignalized median openings.

Mode	Operations	Safety
[car]	Increasing the median width to provide storage space for minor street left-turning vehicles allows those vehicles to complete the maneuver in two stages, increasing the left-turn capacity and reducing delay (*1, 2*). Left-turn acceleration lanes substantially reduce delay for the second stage of a two-stage left turn (*3*). Providing steady flow for one direction by using channelizing islands may eliminate the need for signalizing a three-leg median opening.	Increasing the median width slightly reduces the crash rate at rural intersections (*3*, *4*) but slightly increases it at urban intersections (*4*). Increasing raised median width decreases the crash rate along urban and suburban arterials (*5*). Offset left-turn lanes (*3*) and very wide medians (*4*) at rural intersections may increase the potential for wrong-way movements. Left-turn deceleration lane channelization prevents unexpected maneuvers back into the through lane (*6*) but may cause drivers to begin their acceleration sooner, increasing the speed differential between left-turning vehicles and through vehicles (*3*). Left-turn acceleration lane channelization reduces the speed differential between minor street left turns and through vehicles, improving safety for minor street left turns, but the reduction in the left-turn lane offset may decrease safety for major street left turns (*3*).
[pedestrian]	Increasing the median width to provide a pedestrian refuge allows two-stage pedestrian crossings, reducing pedestrian delay (*1, 2*). Sufficiently wide channelizing islands used to create offset left-turn lanes can also act as pedestrian refuges (*1*).	Sufficiently wide pedestrian refuges and islands provide pedestrian refuge (*1, 4*). Increasing raised median and two-way left-turn lane width decreases the pedestrian crash rate along urban and suburban arterials (*5*). Steady-flow designs prevent the potential for establishing a pedestrian crossing.
[bicycle]	No direct effect. See Chapter 1.	Steady-flow designs require bicyclists to make a left turn as a vehicle (i.e., no option to cross as a pedestrian).
[bus]	Similar to motor vehicles.	No documented effect beyond that generally observed for motor vehicle traffic.
[truck]	Similar to motor vehicles.	Left-turn acceleration lanes have been installed specifically in situations where insufficient median width exists to store trucks (*3*).

Table 16. Crash rate ratios for various speed differentials on rural highways.

Speed Differential (mph)	Crash Rate Ratio Relative to no Speed Differential
0	1.0
–10	2.0
–20	6.5
–30	45
–35	180

Source: Solomon (*7*), Stover and Koepke (*8*).

- Urban and suburban, three-leg unsignalized: 1.03 (all severities)
- Urban and suburban, four-leg signalized: 1.03 (all severities), 1.03 (injury)

The HSM also provides a CMF of 0.73 for providing a channelized left-turn lane for the major roadway at a rural 3-leg intersection on a 2-lane highway (*4*).

NCHRP Report 650 (*3*) summarized the results of a limited number of previous studies on the safety of left-turn acceleration lanes. The general trend in these studies indicated improved overall safety, but potential biases in the study designs (e.g., regression to the mean) prevent making definitive conclusions.

NCHRP Report 650 (*3*) also summarized the results of North Carolina studies of offset left-turn lanes, which found a reduction in left-turn-leaving crashes but an increase in rear-end crashes. Due to potential biases in the study designs (e.g., other simultaneous improvements, changes in traffic volumes, regression to the mean), no definitive conclusions can be drawn.

Table 16 gives crash rate ratios for various speed differentials on rural highways, relative to no speed differential. For example, the crash rate with a 10-mph speed differential is twice the crash rate with no speed differential (*7*, *8*).

The vehicle–vehicle crash prediction model developed by Bowman et al. (*5*) for urban and suburban arterials with raised medians indicates that the crash rate increases as the number of median crossovers increases. The crash rate decreases with increasing raised median width. The appendix provides more details about this model.

Pedestrian Operations

Chapter 20 in the HCM6 can be used to compare pedestrian delay with and without a two-stage pedestrian crossing (*2*). This delay can also be used in Chapter 18 in the HCM6 to determine the change, if any, in pedestrian LOS.

Pedestrian Safety

The vehicle–pedestrian crash prediction models developed by Bowman et al. (*5*) for urban and suburban arterials with raised medians and two-way left-turn lanes indicated that the crash rate decreased with increasing raised median width and when the two-way left-turn lane width increased from 12 feet to 14 feet. The appendix provides more details about these models.

Additional Information

- Chapters 1 and 9 in this guide.
- *Access Management Manual,* Second ed.: Section 17.3.

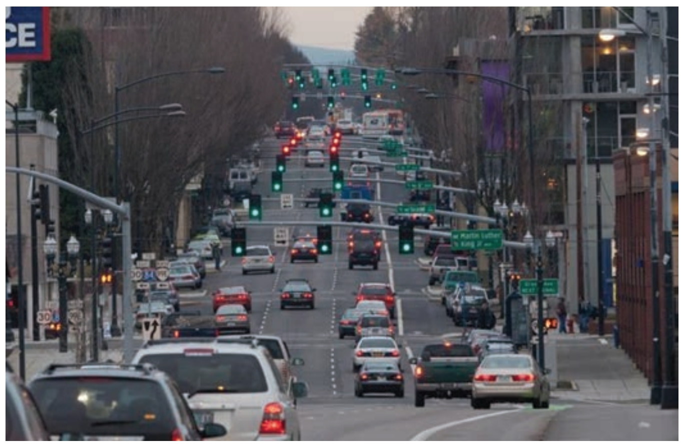
- *Access Management Application Guidelines*: Chapter 15, Median Applications and Design.
- *Median Handbook:* Chapter 2, Important Concepts of Medians and Median Openings Placement (Florida DOT).

References

1. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
2. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
3. Maze, T. H., J. L. Hochstein, R. R. Souleyrette, H. Preston, and R. Storm. *NCHRP Report 650: Median Intersection Design for Rural High-Speed Divided Highways.* Transportation Research Board of the National Academies, Washington, D.C., 2010.
4. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
5. Bowman, B., R. Vecellio, and J. Miao. Vehicle and Pedestrian Accident Models for Median Locations. *Journal of Transportation Engineering,* Vol. 121, No. 6, American Society of Civil Engineers, Washington, D.C., Nov.–Dec. 1994, pp. 531–537.
6. Gluck, J., H. S. Levinson, and V. Stover. *NCHRP Report 420: Impacts of Access Management Techniques.* Transportation Research Board, Washington, D.C., 1999.
7. Solomon, D. H. *Accidents on Main Rural Highways Related to Speed, Driver, and Vehicle.* Bureau of Public Roads, Washington, D.C., 1964.
8. Stover, V. G., and F. J. Koepke, *Transportation and Land Development,* 2nd ed., Institute of Transportation Engineers, Washington, D.C., 2002.

CHAPTER 6

Traffic Signal Spacing



Source: Photograph provided by the authors.

Description

A desired uniform traffic signal spacing is defined and implemented over time. Techniques in this group influence the spacing of traffic signals along a roadway by managing where a new traffic signal may be installed. Long, uniform traffic signal spacing facilitates the ability to provide two-way traffic progression under a variety of traffic conditions (*1*, *2*). Minimum progression bandwidths are defined as part of the criteria (e.g., to be considered when deviations to the desired spacing are being evaluated).

Tables 17 through 21 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

Chapter 16 in the HCM6 (*4*) can be used to estimate the travel time impacts of traffic signal spacing and location on motor vehicle travel times. *NCHRP Report 420* (*3*) provides estimates of the percent increase in travel times when traffic signal spacing is greater than two signals per mile (see Table 20).

Motor Vehicle Safety

NCHRP Report 420 reported average crash rates (crashes per million vehicle miles) by different ranges of traffic signal densities (*3*) (see Table 21).

Table 17. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
										
Lengthen traffic signal spacing.	↑ ●	↓ ●	↕ ●	↕ ●	↑ ●	↑ ●	↓ ◐	↕ ●	○	○
Locate new driveway opposite existing signalized driveway.	↑ ●	○	○	○	○	↑ ●	○ ○	○	○	○
Locate new high-volume driveways where signal spacing criteria can be met.	↕ ●	↑ ●	↕ ●	○	○	↕ ●	↑ ◐	○	○	○
Design driveways and medians such that signals only affect one side of arterial at a time.	↑ ●	↑ ●	○	↑ ◐	↑ ◐	↑ ◐	↑ ◐	○	○	○

Table 18. General trends associated with longer traffic signal spacing.

Mode	Operations	Safety
	Motor vehicle travel speeds are higher by 2 to 3 mph with each one-signal-per-mile reduction in the signal density when signals are closely or irregularly spaced (*1*, *3*).	The crash rate of the motorized vehicle decreases (*1*, *3*).
	Small negative effect on pedestrian LOS due to increased motor vehicle speeds (*4, 5*). When midblock crossings are illegal or experience high delays, pedestrian LOS decreases due to the longer detour required to walk to the nearest signalized intersection (*4, 5*).	Increases in vehicle speeds may negatively affect pedestrian safety (*6*, *7*).
	Bicycle LOS worsens due to increased motor vehicle speeds, which negatively affect bicycle LOS (*4, 5*). Average bicycle travel speeds increase with fewer signals per mile (*4*).	Increases in vehicle speeds may negatively affect bicycle safety (*6*, *7*).
	Similar to motor vehicles, but with greater benefit for buses, as they accelerate more slowly to their running speed after stopping or slowing (*8*). Schedule reliability improves (*9*). Increases the need for bus stops between signalized intersections to minimize passenger walking distances; these stops may be difficult for passengers to access by crossing the street (*10*).	No documented effect beyond that generally observed for motor vehicle traffic and pedestrians.
	Similar to motor vehicles, but with greater benefit for trucks, as they accelerate more slowly to their running speed after stopping or slowing (*11*). Improved truck LOS due to improved speeds (*12*).	No documented effect beyond that generally observed for motor vehicle traffic.

Table 19. General trends associated with providing traffic progression.

Mode	Operations	Safety
	Reduces traffic signal delay and number of stops, thus improving overall travel time (*4*). Improves fuel economy and air quality (*6*). Helps create gaps in traffic that can be used by turning vehicles (*13*).	The motorized vehicle crash rate decreases (*6*).
	Helps create gaps in traffic that can be used by crossing pedestrians.	Helps create gaps in traffic that can be used by crossing pedestrians.
	No documented effect.	No documented effect.
	When bus stops are located on the far side of signalized intersections, buses can take advantage of motor vehicle progression provided along a corridor, resulting in reduced and less variable travel times (*9*).	No documented effect beyond that generally observed for motor vehicle traffic.
	Similar to motor vehicles, but with greater benefit for trucks, as they accelerate more slowly to their running speed after stopping or slowing (*11*).	No documented effect beyond that generally observed for motor vehicle traffic.

Table 20. Percent increase in travel times.

Signals per Mile	Increase in Travel Times Relative to Two Signals Per Mile (%)
3	9
4	16
5	23
6	29
7	34
8	39

Table 21. Average crash rates by different ranges of traffic signal densities.

Signals per Mile	Crash Rate (crashes per million vehicle miles)
≤ 2	3.5
2.01–4	6.9
4.01–6	7.5
> 6	9.1

Data from southeast Michigan indicate that providing signal progression reduces the number of collisions in a corridor by 10% to 20% (*6*).

Pedestrian Operations

Equations 18-32 and 18-35 in the HCM6 (*4*) can determine the effect of motorized vehicle speeds on pedestrian link LOS. An increase in average traffic speed of 2 mph worsens the pedestrian link LOS score by 0.03 points (at 20 mph) to 0.08 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter.

Increasing the traffic signal spacing may reduce pedestrian LOS in situations when no legal pedestrian crossings are available between signals or when the pedestrian delay experienced waiting for a safe gap to cross the street is greater than the time required to detour to the nearest signalized crossing (*8*). The impact on the pedestrian LOS score depends on the change in delay for pedestrians and the quality of the pedestrian environment along the roadway ("link") and at signalized intersections. Greater delays and poorer link and intersection pedestrian environments result in greater reductions in the pedestrian LOS score. Chapter 18 in the HCM6 describes the methodology.

Bicycle Operations

Equations 18-41 and 18-44 in the HCM6 (*4*) can determine the effect of motorized vehicle speeds on bicycle LOS. An increase in average traffic speed of 2 mph worsens the bicycle LOS score by 0.57 points (at 21 mph or less), 0.17 points (at 25 mph), 0.05 points (at 40 mph), and 0.03 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter.

The bicycle methodology in Chapter 18 in the HCM6 can be used to estimate the impact of traffic signal delays on overall bicycle travel times along a roadway (*4*).

Bicycle Safety

Carter et al. (*14*) developed a model to predict a bicycle intersection safety index. The index value for through bicycle movements worsens by 0.428 rating points if a traffic signal were installed and no bicycle lane was present. The index value for left-turning movements worsens by 0.485 ratings points if a traffic signal were installed. See the appendix for more details about this model.

Bus Operations

Chapter 18 in the HCM6 (*4*) can be used to estimate the change in average bus speeds resulting from changes in signal spacing and intersection delay. This information in turn can estimate the change in bus LOS for the segment. At 30-minute bus headways and with seated loads and reliable service, a 1-mph increase in average bus speed produces a 0.08–0.12 improvement in the bus LOS score, with 0.75 points representing the range covered by one LOS letter (*4*, *10*).

Truck Operations

Section P in Exhibit 3 of *NCHRP Report 825* (*15*), derived from *NCFRP Report 31* (*12*), can be used to estimate the effect of improved truck free-flow and travel speeds on overall truck LOS. On a level street with a 35-mph free-flow speed, increasing average truck speeds from 25 to 26 mph results in a 1.3 percentage point increase in the truck LOS index, while increasing average truck speeds from 17.5 to 18.5 mph results in a 7.0 percentage point increase, with 10 percentage points representing the range covered by one LOS letter.

Additional Information

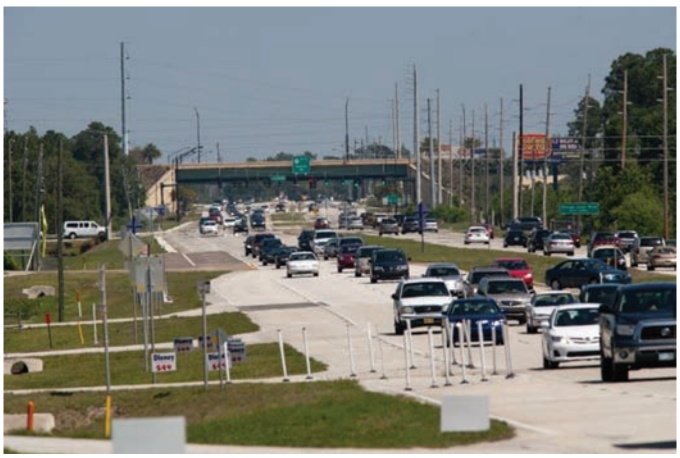
- Chapter 12 in this guide.
- *Access Management Manual,* Second ed.: Sections 15.2 and 20.2.1.
- *Access Management Application Guidelines*: Chapter 13, Signalized Access Spacing.
- *NCHRP Report 420*: Chapter 3, Traffic Signal Spacing.

References

1. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
2. Stover, V. G., and F. J. Koepke, *Transportation and Land Development,* 2nd ed., Institute of Transportation Engineers, Washington, D.C., 2002.
3. Gluck, J., H. S. Levinson, and V. Stover. *NCHRP Report 420: Impacts of Access Management Techniques.* Transportation Research Board, Washington, D.C., 1999.
4. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
5. Dowling, R., D. Reinke, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, N. Rouphail, and J. Bonneson. *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
6. Chandler, B. E., M. C. Myers, J. E. Atkinson, T. E. Bryer, R. Retting, J. Smithline, J. Trim, P. Wojtkiewicz, G. B. Thomas, S. P. Venglar, S. Sunkari, B. J. Malone, and P. Izadpanah. *Signalized Intersections Informational Guide,* 2nd ed. Publication No. FHWA-SA-13-027. Federal Highway Administration, Washington, D.C., July 2013.
7. National Association of City Transportation Officials. *Urban Street Design Guide.* National Association of City Transportation Officials, Washington, D.C., Oct. 2013.
8. Hemily, B., and R. D. King. *TCRP Synthesis 75: Uses of Higher Capacity Buses in Transit Service.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
9. Ryus, P., K. Laustsen, K. Blume, S. Beaird, and S. Langdon. *TCRP Report 183: A Guidebook on Transit-Supportive Roadway Strategies.* Transportation Research Board, Washington, D.C., 2016.
10. Kittelson & Associates, Inc.; Parsons Brinckerhoff; KFH Group, Inc.; Texas A&M Transportation Institute; and Arup. *TCRP Report 165: Transit Capacity and Quality of Service Manual,* 3rd ed. Transportation Research Board of the National Academies, Washington, D.C., 2013.
11. Harwood, D. W., D. J. Torbic, K. R. Richard, W. D. Glauz, and L. Elefteriadou. *NCHRP Report 505: Review of Truck Characteristics as Factors in Roadway Design.* Transportation Research Board of the National Academies, Washington, D.C., 2003.
12. Dowling, R., G. List, B. Yang, E. Witzke, and A. Flannery. *NCFRP Report 31: Incorporating Truck Analysis into the Highway Capacity Manual*. Transportation Research Board of the National Academies, Washington, D.C., 2014.
13. Antonucci, N. D., K. K. Hardy, K. L. Slack, R. Pfefer, and T. R. Neuman. *NCHRP Report 500: Guidance for Implementation of the AASHTO Strategic Highway Safety Plan, Volume 12: A Guide for Reducing Collisions at Signalized Intersections*. Transportation Research Board of the National Academies, Washington, D.C., 2004.
14. Carter, D. L., W. W. Hunter, C. V. Zegeer, J. R. Stewart, and H. F. Huang. *Pedestrian and Bicyclist Intersection Safety Indices: Final Report.* Report FHWA-HRT-06-125. Federal Highway Administration, Washington, D.C., Nov. 2006.
15. Dowling, R., P. Ryus, B. Schroeder, M. Kyte, T. Creasey, N. Rouphail, A. Hajbabaie, and D. Rhoades. *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual.* Transportation Research Board, Washington, D.C., 2016.

CHAPTER 7

Number and Spacing of Unsignalized Access Points



Source: Photograph provided by the authors.

Description

This group includes a range of techniques to reduce the number of access points along a roadway, increase the spacing between unsignalized access points, or both. The minimum distances along a roadway between two successive unsignalized connections and between roadway intersections and the nearest access point (i.e., corner clearance) are established and implemented over time. The relative locations of access points on opposite sides of the roadway can also be established.

Tables 22 through 26 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

Equations 18-3 and Exhibit 18-11 in the HCM6 give the reduction in roadway free-flow speed due to access point density (*2*). This reduction (in mph) equals $-0.078\ D_a/N_{th}$, where D_a is the number of access points per mile (considering both sides of the roadway, but only those accessible to or from the direction of travel) and N_{th} is the number of through lanes in the direction of travel. The resulting increase in average travel speed will be slightly lower, as discussed in the appendix.

Exhibit 18-13 in the HCM6 gives average through vehicle delay in terms of seconds per vehicle per full, unsignalized access point (*2*) (see Table 25).

Table 22. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
	🚗	🚶	🚲	🚌	🚚	🚗	🚶	🚲	🚌	🚚
Increase the spacing between adjacent access points.	↑ ◐	○	○	○	○	↑ ◐	↑ ◐	↑ ◐	↑ ◐	○
Increase corner clearance.	↑ ●	○	○	↑ ◐	○	↑ ◐	○	○	○	○
Consolidate driveways.	↑ ●	↓ ●	↕ ●	↑ ◐	↑ ◐	↑ ●	↕ ●	↕ ◐	○	○
Coordinate driveways on opposite sides of roadway.	↔ ●	○	○	○	○	↑ ◐	○	○	○	○
Provide connections between adjacent properties.	↑ ●	↕ ●	↕ ●	○	○	↑ ◐	↕ ◐	↕ ◐	○	○
Require access on collector (if available) in lieu of arterial.	↑ ●	↕ ●	↕ ●	↑ ◐	↑ ◐	↑ ●	↕ ◐	↕ ◐	○	○
Relocate or reorient access.	↑ ◐	○	○	↑ ◐	○	↑ ◐	○	○	↑ ◐	○

Note: ↔ = unchanged performance.

Table 23. General trends associated with reducing the number of unsignalized access points.

Mode	Operations	Safety
🚗	Motor vehicle free flow and travel speeds increase by up to a few miles per hour. Speed increases are greater when the number of through lanes is less, when through traffic volumes are higher, and when turning traffic volumes are higher (*1, 2*). Longer distances between access points provide space to provide turn lanes (*3, 4*).	The motorized vehicle crash rate decreases (*5, 6*). The number of vehicle–vehicle conflict points decreases.
🚶	Small negative effect on pedestrian LOS due to increased motor vehicle speeds (*2, 10*).	The number of vehicle–pedestrian conflict points decreases (*4*). Increases in vehicle speeds may negatively affect pedestrian safety (*8*, *9*).
🚲	Bicycle LOS improves due to the reduction in the number of access points. This improvement is partially (or wholly, at traffic speeds less than 25 to 30 mph) offset by the increase in motor vehicle speeds, which negatively affects bicycle LOS (*2*, *7*).	The number of potential vehicle–bicycle conflict points decreases (*4*). Increases in vehicle speeds may negatively affect bicycle safety (*8*, *9*).
🚌	Similar to motor vehicles but with greater benefit for buses, as they accelerate more slowly to their running speed after stopping or slowing (*10*). Greater flexibility for selecting bus stop locations (*4*).	No documented effect beyond that generally observed for motor vehicle traffic.
🚚	Similar to motor vehicles but with greater benefit for trucks, as they accelerate more slowly to their running speed after stopping or slowing (*11*). Improved truck LOS due to improved speeds (*12*).	No documented effect beyond that generally observed for motor vehicle traffic.

Table 24. General trends associated with managing access spacing and location.

Mode	Operations	Safety
	Longer corner clearances reduce the chance of an access being blocked due to downstream intersection queues (*4*). Longer distances between access points provide sufficient distance for motorists exiting an access to maneuver to make a turn at a downstream intersection or crossover (*13*). Inter-parcel connections reduce driving time between adjacent sites and potentially reduce the need to drive between sites.	Longer access spacing minimizes the number of locations motorists must monitor at a given time (*4*) and avoids multiple access connections to a single right-turn lane that make it unclear which access a vehicle will turn into (*3*). On undivided roadways or roadways with a two-way left-turn lane, coordinating access points on opposite sides of the roadway avoids left-turn conflicts between vehicles traveling in opposite directions and avoids jog maneuvers when crossing the roadway (*3*). As many as half of the crashes within the functional area of an intersection may be driveway-related (*5, 6*); these can be reduced or eliminated by using corner clearance standards.
	Providing inter-parcel pedestrian connections reduces travel time between adjacent sites and can reduce traffic on the arterial.	With longer access spacing, motorists have fewer distractions and can focus on activity occurring at a given access, including pedestrians crossing or approaching the access. Inter-parcel pedestrian connections can reduce the number of required driveway and aisle crossings while traveling between adjacent sites (*4*).
	Providing inter-parcel bicycle connections reduces travel time between adjacent sites and can reduce traffic on the arterial.	With longer access spacing, motorists have fewer distractions and can focus on activity occurring at a given access, including bicyclists crossing or approaching the access. Inter-parcel bicycle connections allow travel on lower-volume roadways while traveling between adjacent sites (*4*).
	Corner clearance standards can be developed to incorporate sufficient space for a bus stop at intersections, providing convenient access for bus passengers.	Access spacing standards can ensure that sufficient space is provided between driveways to develop bus stops that do not block sight distance from driveways when the bus stop is occupied (*4*).
	Similar to motor vehicles.	Similar to motor vehicles.

Table 25. Average through vehicle delay in terms of seconds per vehicle per full, unsignalized access point.

Midsegment Volume (vehicles per hour per lane)	Through Vehicle Delay (seconds per vehicles per access point) by Number of Through Lanes		
	1 Lane	2 Lanes	3 Lanes
200	0.04	0.04	0.05
300	0.08	0.08	0.09
400	0.12	0.15	0.15
500	0.18	0.25	0.15
600	0.27	0.41	0.15
700	0.39	0.72	0.15

Table 26. Percentage of cycles.

Flow in Lane Adjacent to Driveway (vehicles per hour)	Duration of Red Phase (seconds)	Percentage of Cycles, by Corner Clearance				
		25 feet	50 feet	75 feet	100 feet	125 feet
200	15	20	5	1	na	na
	25	40	16	5	na	na
	35	58	31	13	5	2
	45	71	46	24	11	4
400	15	50	23	9	3	1
	25	77	53	30	15	6
	35	90	75	55	35	20
	45	96	88	74	56	38

Note: Assumes that the average vehicle length, including the space between stopped vehicles, is 25 feet; na = not applicable.
Source: Access Management Manual, Second ed., Exhibit 15-39 (*3*), adapted from Stover and Koepke (*14*).

Delay values in Table 25 assume 10% of the traffic on the street turns right at the access point and 10% turns left. Adjust the delay values proportionately for other turning percentages. Reduce the delay values by 50% if one turning movement is provided with an appropriately dimensioned turn lane or the turning movement does not exist. There is no delay if both turning movements are provided with turn lanes (or if one movement has a turn lane and the other movement does not exist). See Chapters 9 and 10 for additional information specific to turn lanes.

The *Access Management Manual*, Second ed. identified the percentage of cycles during which a driveway in proximity to a signalized intersection will be blocked (*3*, *14*) (see Table 26).

Motor Vehicle Safety

Drawing from a review of a number of crash studies, *NCHRP Report 420* (*6*) indicated that each additional access point per mile increased a roadway's crash rate by 4%, relative to the crash rate experienced at 10 access points per mile (total of both sides). Thus, a road with 60 access points per mile would be expected to have 200% more (i.e., three times as many) crashes as one with 10 access points per mile.

The HSM provides the following crash modification factors related to urban and suburban arterials in Table 13-58 (*5*):

- Reducing driveways from 48 to 26–48 per mile: 0.71
- Reducing driveways from 26–48 to 10–24 per mile: 0.69
- Reducing driveways from 10–24 to less than 10 per mile: 0.75

A recent study in South Carolina (*15*) found that increasing the spacing between driveways decreases the crash rate at driveways.

Pedestrian Operations

Equations 18-32 and 18-35 in the HCM6 (*2*) can determine the effect of motorized vehicle speeds on pedestrian link LOS. An increase in average traffic speed of 2 mph worsens the pedestrian link LOS score by 0.03 points (at 20 mph) to 0.08 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter. Unsignalized access spacing was not found to be a significant predictor of ratings of pedestrian LOS (*7*).

Pedestrian Safety

Bowman et al. (*16*) developed a predictive model for streets with a raised-curb median. The model relates crash rate to driveway density and indicates that the vehicle–pedestrian crash rate increases with an increase in driveway density.

Bicycle Operations

Equations 18-41 and 18-44 in the HCM6 (*2*) are used to determine the effect of motorized vehicle speeds on bicycle LOS along a roadway link (i.e., between traffic signals). An increase in average traffic speed of 2 mph worsens the bicycle LOS score by 0.57 points (at 21 mph or less), 0.17 points (at 25 mph), 0.05 points (at 40 mph), and 0.03 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter.

Equations 18-46 and 18-47 in the HCM6 (*2*) can determine the effect of right-side unsignalized access density on bicycle LOS along a roadway segment (i.e., considering both the link and its downstream traffic signal). Decreasing the access point density by 10 points per mile improves bicycle LOS by 0.00–0.77 points per mile, with greater improvements occurring when (a) the starting access point density is higher and (b) the starting bicycle LOS for the link is worse. These results assume that the roadway link and the downstream, signalized intersections have identical bicycle LOS scores.

Truck Operations

Section P in Exhibit 3 of *NCHRP Report 825* (*17*), derived from *NCFRP Report 31* (*12*), can be used to estimate the effect of improved truck free-flow and travel speeds on overall truck LOS. On a level street with a 35-mph free-flow speed, increasing average truck speeds from 25 to 26 mph results in a 1.3 percentage point increase in the truck LOS index, while increasing average truck speeds from 17.5 to 18.5 mph results in a 7.0 percentage point increase, with 10 percentage points representing the range covered by one LOS letter.

Additional Information

- Chapters 6, 8, 9, and 10 in this guide.
- *Access Management Manual,* Second ed.: Sections 15.3, 15.4, and 20.2.
- *Access Management Application Guidelines*: Chapter 12, Unsignalized Access Spacing.
- *NCHRP Report 420*: Chapter 4, Unsignalized Access Spacing, and Chapter 5, Corner Clearance Criteria.

References

1. Texas Transportation Institute; Kittelson & Associates, Inc.; and Purdue University. *Predicting the Performance of Automobile Traffic on Urban Streets.* Final report, NCHRP Project 03-79. Transportation Research Board of the National Academies, Washington, D.C., Jan. 2008.
2. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
3. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
4. Dixon, K. K., R. D. Layton, M. Butorac, P. Ryus, J. L. Gattis, L. Brown, and D. Huntington. *Access Management Application Guidelines.* Transportation Research Board, Washington, D.C., 2016.
5. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.

6. Gluck, J., H. S. Levinson, and V. Stover. *NCHRP Report 420: Impacts of Access Management Techniques.* Transportation Research Board, National Academy Press, Washington, D.C., 1999.
7. Dowling, R., D. Reinke, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, N. Rouphail, and J. Bonneson. *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
8. Chandler, B. E., M. C. Myers, J. E. Atkinson, T. E. Bryer, R. Retting, J. Smithline, J. Trim, P. Wojtkiewicz, G. B. Thomas, S. P. Venglar, S. Sunkari, B. J. Malone, and P. Izadpanah. *Signalized Intersections Informational Guide,* 2nd ed. Publication No. FHWA-SA-13-027. Federal Highway Administration, Washington, D.C., July 2013.
9. National Association of City Transportation Officials. *Urban Street Design Guide.* National Association of City Transportation Officials, Washington, D.C., Oct. 2013.
10. Hemily, B., and R. D. King. *TCRP Synthesis 75: Uses of Higher Capacity Buses in Transit Service.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
11. Harwood, D. W., D. J. Torbic, K. R. Richard, W. D. Glauz, and L. Elefteriadou. *NCHRP Report 505: Review of Truck Characteristics as Factors in Roadway Design.* Transportation Research Board of the National Academies, Washington, D.C., 2003.
12. Dowling, R., G. List, B. Yang, E. Witzke, and A. Flannery. *NCFRP Report 31: Incorporating Truck Analysis into the Highway Capacity Manual*. Transportation Research Board of the National Academies, Washington, D.C., 2014.
13. Gan, C.-T., and G. Long. Effects of Inadequate Driveway Corner Clearances on Traffic Operations, Safety, and Capacity. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1579, 1997, pp. 35–42.
14. Stover, V. G., and F. J. Koepke, *Transportation and Land Development,* 2nd ed. Institute of Transportation Engineers, Washington, D.C., 2002.
15. Stokes, A., W. A. Sarasua, N. Huynh, K. Brown, J. H. Ogle, A. Mammadrahimli, W. J. Davis, and M. Chowdhury. Safety Analysis of Driveway Characteristics Along Major Urban Arterial Corridors in South Carolina. Presented at 95th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 2016.
16. Bowman, B., R. Vecellio, and J. Miao. Vehicle and Pedestrian Accident Models for Median Locations. *Journal of Transportation Engineering,* Vol. 121, No. 6, American Society of Civil Engineers, Washington, D.C., Nov.–Dec. 1994, pp. 531–537.
17. Dowling, R., P. Ryus, B. Schroeder, M. Kyte, T. Creasey, N. Rouphail, A. Hajbabaie, and D. Rhoades. *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual.* Transportation Research Board, Washington, D.C., 2016.

CHAPTER 8

Interchange Areas

Source: Photograph provided by the authors.

Description

These techniques are applied to interchange crossroads to adequately separate access points from interchange ramp terminals. Minimum distances are specified from an interchange ramp terminal to the first downstream and last upstream (*1*): driveway, unsignalized crossroad intersection, median opening, and signalized intersection.

Tables 27 through 29 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

No national research on arterial weaving operations has been completed at the time of writing, although NCHRP Project 15-66, "Arterial Weaving on Conventional and Alternative Intersections," will address the topic. The table from *NCHRP Report 420* (*3*, *4*) can be used to estimate the minimum distance required to make a weaving maneuver from the right lane to the left lane (e.g., from a free-flowing right-turn lane from an off-ramp to a downstream left-turn lane). The minimum separation distance should be greater than the sum of the weaving distance, the distance required to transition into a left-turn lane and come to a stop, and the 95th-percentile queue length in the left-turn lane (see Table 29).

Methods in HCM6 (*5*) can be used to estimate the 95th percentile queue at a traffic signal by movement; the distance between a downstream signal and an off-ramp should be greater

Table 27. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships: Operations					Safety				
										
Increase access separation distances in interchange areas.	↑ ●	↔ ●	↔ ●	○	○	↑ ◐	↑ ◐	↑ ◐	○	○

Note: See Chapter 7 for performance trends generally associated with increasing access separation distances. ↔ = unchanged performance.

Table 28. General trends associated with increasing access separation distance at interchanges.

Mode	Operations	Safety
	Provides more distance to make weaving maneuvers between free-flowing off-ramps and downstream left-turn lanes (*1*). Reduces the chance that queues will back up into the ramp terminal intersection, the ramp, or the freeway (*1*). Provides a better opportunity to time signals to progress traffic (*1*). See also Chapter 6.	Improves safety by reducing the number of conflicts and decisions to be made in a potentially high-volume, complex, and unfamiliar environment. As a result, the potential for sudden decisions leading to erratic maneuvers is reduced (*1*, *2*).
	No change in pedestrian LOS beyond that generally associated with increasing access spacing. See also Chapter 7.	Improves safety by reducing the number of potential motorist distractions in advance of pedestrian crossings of on-ramps. Interchange design influences pedestrian safety (*2*). See also Chapters 7 and 12.
	No change in bicycle LOS beyond that generally associated with increasing access spacing. See also Chapter 7.	Similar effects as for pedestrians.
	No documented effect beyond that observed for motor vehicle traffic generally.	No documented effect beyond that generally observed for motor vehicle traffic.
	No documented effect beyond that observed for motor vehicle traffic generally.	No documented effect beyond that generally observed for motor vehicle traffic.

Table 29. Minimum distance required to make a weaving maneuver from the right lane to the left.

Weaving Volume (vehicles per hour)	Speed (mph): 25, 30	35	40	45	50
200	50	100	150	200	400
400	100	200	300	450	800
600	150	300	450	700	1,200
800	200	400	600	950	1,800
1,000	300	500	750	1,200	2,400
1,200	350	600	900	1,450	[a]
1,400	400	710	1,050	1,700	[a]
1,600	450	820	1,200	2,050	[a]
1,800	500	930	1,400	2,400	[a]
2,000	600	1,040	1,600	[a]	[a]
2,200	700	1,150	1,800	[a]	[a]
2,400	800	1,270	2,050	[a]	[a]
2,600	900	1,400	2,300	[a]	[a]

Note: Use 400 feet for values above the solid line.
[a]Speeds are not attainable.
Source: NCHRP Report 420, Table 85 (*3*), adapted from Leisch (*4*).

than this length to avoid frequent queue spillback onto the ramp and, potentially, onto the freeway.

The *Access Management Manual,* Second ed. (*1*) and *Access Management Application Guidelines* (*2*) provide recommended access spacing distances at interchanges.

Pedestrian and Bicycle Operations

Quantitative methods for the pedestrian and bicycle modes near interchanges are the same as for arterials in general. See Chapter 7 for details.

Pedestrian and Bicycle Safety

Section 18.6 of the *Access Management Manual*, Second ed. (*1*) provides guidance on designing interchanges to safely accommodate pedestrians and bicyclists. Free-flow ramps are discouraged because they are difficult for pedestrians and bicyclists to cross safely, due to a combination of relatively high vehicular speeds, infrequent gaps in traffic, and the potentially unexpected nature of a pedestrian or bicycle crossing. Based on California research, the HSM states that "encouraging bicyclists to cross interchange ramps at right angles appears to increase driver sight distance and reduce the bicyclists' risk of a crash" (*6*).

Additional Information

- Chapters 6, 7, and 12 in this guide.
- *Access Management Manual,* Second ed.: Chapter 18, Interchange Area Access Management.
- *Access Management Application Guidelines*: Chapter 18, Access Management at Crossroads in the Vicinity of Interchanges.
- *NCHRP Report 420*: Chapter 9, Access Separation at Interchanges.

References

1. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
2. Dixon, K. K., R. D. Layton, M. Butorac, P. Ryus, J. L. Gattis, L. Brown, and D. Huntington. *Access Management Application Guidelines.* Transportation Research Board, Washington, D.C., 2016.
3. Gluck, J., H. S. Levinson, and V. Stover. *NCHRP Report 420: Impacts of Access Management Techniques.* Transportation Research Board of the National Academies, Washington, D.C., 1999.
4. Leisch, J. E. *Procedure for Analysis and Design of Weaving Sections.* Project DT FHS 1-82-1-00050. Federal Highway Administration, Washington, D.C., 1982.
5. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
6. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.

CHAPTER 9

Left-Turn Lanes

Source: Photograph provided by the authors.

Description

A *left-turn lane* is typically an auxiliary lane in the middle of a two-way roadway. Left-turn deceleration lanes allow left-turning vehicles from the roadway to conduct most of their deceleration and, if necessary, queue and wait for a safe gap in opposing traffic before turning.

Tables 30 through 35 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

The table from *NCHRP Report 745* (*3*) gives intersection-wide delay reductions resulting from adding a left-turn lane at an unsignalized intersection, developed from simulation (see Table 32).

Chapters 19 and 20 in the HCM6 can be used to compare the change in delay as a result of installing left-turn lanes (*2*), in cases in which the left-turn lane is adequately sized to prevent queue spillback into the through lanes.

Chapter 31, Section 4, in the HCM6 can be used to calculate a desired percentile back-of-queue for left-turn lanes at signalized intersections, while Equation 20-68 in Chapter 20 in the HCM6 can be used to determine the 95th percentile queue length for the left-turn lanes on major-street approaches to two-way stop-controlled intersections (*2*). A taper distance, allowing vehicles to maneuver from the through lane into the left-turn lane, and a deceleration distance

Table 30. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
										
Install left-turn deceleration lanes where none exists.	↑ ●	↓ ●	↓ ●	↑ ◐	↑ ●	↑ ●	↓ ◐	↓ ◐	↑ ◐	○
Install alternating left-turn lane.	↑ ●	↓ ●	↓ ●	↑ ◐	↑ ●	↑ ●	↓ ◐	↓ ◐	↑ ◐	○
Install isolated median and left-turn lane to shadow and store left-turn vehicles.	↑ ●	↓ ●	↓ ●	↑ ◐	↑ ●	↑ ●	↓ ◐	↓ ◐	↑ ◐	○
Install left-turn deceleration lane in lieu of right-angle crossover.	○	○	○	○	○	○	○	○	○	○
Increase storage capacity of existing left-turn lane.	↑ ●	○	○	○	○	↑ ●	○	○	○	○

Table 31. General trends associated with providing left-turn lanes.

Mode	Operations	Safety
	Motor vehicle free-flow and travel speeds increase by up to a few miles per hour. Speed increases are greater when the number of through lanes is less, when through traffic volumes are higher, and when turning traffic volumes are higher (*1–3*).	The motorized vehicle crash rate decreases (*4*).
	Small negative effect on pedestrian LOS due to increased motor vehicle speeds (*2, 5*). At unsignalized intersections, crossing distance and pedestrian delay increase and pedestrian LOS may decrease, if the roadway is widened to install the left-turn lane and no pedestrian refuge is provided (*2, 6*). The traffic signal cycle length may need to increase to accommodate longer pedestrian crossing distances, increasing pedestrian delay (*6*).	Increases pedestrian exposure to traffic if the roadway is widened to install the left-turn lane (*7*).
	If traffic conditions permit bicyclists to access the turn lane, provides easier left turns for bicyclists at unsignalized intersections (*6*).	Increases cross-street bicycle exposure to traffic due to widened cross-section (*6*).
	Improves transit speeds at locations where left-turning traffic blocks through traffic (*7*).	Buses need longer gaps in traffic to make left turns; therefore, a left-turn lane reduces exposure by providing a refuge for buses waiting for a suitable gap (*6*).
	Similar to motor vehicles, but with greater benefit for trucks, as they accelerate more slowly to their running speed after stopping or slowing (*8*). Improved truck LOS due to improved speeds (*9*).	No documented effect beyond that generally observed for motor vehicle traffic.

Table 32. Intersection-wide delay reductions.

Total Major Street Through Lanes	Speed Limit (mph)	Major Street Volume (vehicles per hour per lane)	Intersection Delay Reduction (seconds per vehicle) by Left-Turning Volume (vehicles per hour): 20	60	100	140
2	30	400	0.0	0.4	1.0	1.5
		600	0.7	1.2	1.8	2.4
		800	1.5	2.0	2.6	3.2
	40	400	0.0	0.0	0.6	1.1
		600	0.3	0.8	1.4	1.9
		800	1.1	1.6	2.1	2.7
	50	400	0.0	0.0	0.5	1.0
		600	0.2	0.8	1.3	1.9
		800	1.0	1.6	2.1	2.7
4	30	400	0.0	0.0	0.3	0.6
		600	0.2	0.5	0.8	1.1
		800	0.7	1.0	1.3	1.6
	40	400	0.0	0.0	0.1	0.5
		600	0.0	0.4	0.8	1.2
		800	0.7	1.1	1.5	1.9
	50	400	0.0	0.0	0.1	0.7
		600	0.2	0.7	1.3	[a]
		800	1.3	1.9	2.4	[a]

Note: Define delay reduction based on all vehicles entering the intersection in the hour and assume adequate left-turn storage and deceleration distance.
[a]Beyond the limit of regression, use value scaled from Figures 23 or 24 in *NCHRP Report 745* (*3*).
Source: NCHRP Web-Only Document 193, Table 46 (*10*).

Table 33. Crash modification factors for approaches to four-leg, two-way stop-controlled intersections.

Intersection Type	Traffic Volume: AADT (vehicles per day)	Crash Severity	Crash Modification Factor by Number of Approaches with Left-Turn Lanes: One Approach	Two Approaches
Rural, 4-leg, TWSC	Major: 1,600–32,400	All	0.72	0.52
	Minor: 50–11,800	Injury	0.65	0.42
Urban, 4-leg, TWSC	Major: 1,500–40,600	All	0.73	0.53
	Minor: 200–8,000	Injury	0.71	0.50
Rural, 4-leg, signalized	Unspecified	All	0.82	0.67
Urban, 4-leg, signalized	Major: 1,500–32,400	All	0.90	0.81
	Minor: 50–11,800	Injury	0.91	0.83
Urban, 4-leg, newly signalized	Major: 4,600–40,300	All	0.76	0.58
	Minor: 100–13,700	Injury	0.72	0.52

Note: Values apply to major street approaches at unsignalized intersections and any approach at signalized intersections. For signalized intersections with three or four approaches with left-turn lanes, the crash modification factor is the value for one approach raised to the third or fourth power, respectively. TWSC = two-way stop controlled (minor street stop controlled); AADT = annual average daily traffic.
Source: Highway Safety Manual, 1st ed., Tables 14-11 and 14-12 (*4*).

Table 34. Crash modification factors for approaches to three-leg, two-way stop-controlled intersections.

Intersection Type	Traffic Volume: AADT (vehicles per day)	Crash Severity	Crash Modification Factor
Rural, three-leg, TWSC	Major: 1,600–32,400 Minor: 50–11,800	All Injury	0.56 0.45
Urban, three-leg, TWSC	Major: 1,500–40,600 Minor: 200–8,000	All	0.67
Urban, three-leg, TWSC	Unspecified	Injury	0.65
Rural, three-leg, signalized	Unspecified	All	0.85
Urban, three-leg, signalized	Unspecified	All Injury	0.93 0.94

Note: Values apply to the major street approach at unsignalized intersections and any approach at signalized intersections.
Source: Highway Safety Manual, 1st ed., Table 14-10 (*4*).

need to be added to this storage length when determining the total left-turn lane length. *NCHRP Report 745* (*3*) and the *Access Management Manual* (*11*), among others, provide guidance on designing left-turn lanes. Workbook 11 that accompanies the linked version of the *Access Management: Manual and Application Guidelines* (*12*) is a spreadsheet tool for calculating the total left-turn lane length at signalized intersections.

Motor Vehicle Safety

The HSM provides crash modification factors related to installing left-turn lanes on the major street approaches to four-leg, two-way stop-controlled intersections and on any approach to a four-leg signalized intersection (*4*) (see Table 33).

The HSM also provides crash modification factors for installing a left-turn lane on one major street approach to a three-leg minor street stop-controlled intersection and on any approach to a three-leg signalized intersection (*4*) (see Table 34 above).

An FHWA study (*13*) found an average 43% reduction in crash rates at four rural four-leg unsignalized intersections where left-turn lanes had been lengthened. No information was available about left-turning volumes or overflow from the existing turn lane at the intersections. Sample sizes were too small to permit drawing conclusions about lengthening turn lanes at other types of intersections.

Left-turn lanes that are too short to accommodate demand or that otherwise provide insufficient deceleration distance result in a greater speed differential between left-turning vehicles and through vehicles relative to the typical design differential of 10 mph (*1*). Table 35 (*14*, *15*) gives crash rate ratios for various speed differentials on rural highways relative to no speed differential. For example, the crash rate with a 10-mph speed differential is twice the crash rate with no speed differential.

See Chapter 5 for information related to channelized left-turn lanes.

Pedestrian Operations

Equations 18-32 and 18-35 in the HCM6 (*2*) can determine the effect of motorized vehicle speeds on pedestrian link LOS. An increase in average traffic speed of 2 mph worsens the

Table 35. Crash rate ratios for various speed differentials on rural highways relative to no speed differential.

Speed Differential (mph)	Crash Rate Ratio Relative to no Speed Differential
0	1.0
–10	2.0
–20	6.5
–30	45
–35	180

Source: Solomon (*14*), Stover and Koepke (*15*).

pedestrian link LOS score by 0.03 points (at 20 mph) to 0.08 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter.

Equation 19-72 in the HCM6 (*2*) can determine the effect of intersection width on pedestrian intersection LOS. An increase of one lane of width worsens the pedestrian intersection LOS score by 0.13 points (widening from 7 to 8 lanes, including turn lanes) to 0.23 points (2 to 3 lanes), with 1.00 point representing the range covered by one LOS letter.

Bicycle Operations

Equations 18-41 and 18-44 in the HCM6 (*2*) can determine the effect of motorized vehicle speeds on bicycle link LOS. An increase in average traffic speed of 2 mph worsens the bicycle link LOS score by 0.57 points (at 21 mph or less), 0.17 points (at 25 mph), 0.05 points (at 40 mph), and 0.03 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter.

Equation 19-80 in the HCM6 (*2*) can determine the effect of intersection width on bicycle intersection LOS. An increase in intersection width of 12 feet worsens the bicycle intersection LOS score by 0.18 points, with 1.00 point representing the range covered by one LOS letter.

Truck Operations

Section P in Exhibit 3 of *NCHRP Report 825* (*16*), derived from *NCFRP Report 31* (*9*), can be used to estimate the effect of improved truck free-flow and travel speeds on overall truck LOS. On a level street with a 35-mph free-flow speed, increasing average truck speeds from 25 to 26 mph results in a 1.3 percentage point increase in the truck LOS index, while increasing average truck speeds from 17.5 to 18.5 mph results in a 7.0 percentage point increase, with 10 percentage points representing the range covered by one LOS letter.

Additional Information

- Chapter 5 in this guide.
- *Access Management Manual,* Second ed.: Chapter 16, Auxiliary Lanes, Section 20.3.4.
- *Access Management Application Guidelines*: Chapter 21, Left-Turn Lanes.
- *NCHRP Report 420*: Chapter 7, Left-Turn Lanes.

References

1. Texas Transportation Institute; Kittelson & Associates, Inc.; and Purdue University. *Predicting the Performance of Automobile Traffic on Urban Streets.* Final report, NCHRP Project 03-79. Transportation Research Board of the National Academies, Washington, D.C., Jan. 2008.

2. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
3. Fitzpatrick, K., M. A. Brewer, W. L. Eisele, H. S. Levinson, J. S. Gluck, and M. R. Lorenz. *NCHRP Report 745: Left-Turn Accommodations at Unsignalized Intersections.* Transportation Research Board of the National Academies, Washington, D.C., 2013.
4. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
5. Dowling, R., R. David, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, N. Rouphail, and J. Bonneson. *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
6. Dixon, K. K., R. D. Layton, M. Butorac, P. Ryus, J. L. Gattis, L. Brown, and D. Huntington. *Access Management Application Guidelines.* Transportation Research Board, Washington, D.C., 2016.
7. Ryus, P., K. Laustsen, K. Blume, S. Beaird, and S. Langdon. *TCRP Report 183: A Guidebook on Transit-Supportive Roadway Strategies.* Transportation Research Board, Washington, D.C., 2016.
8. Harwood, D. W., D. J. Torbic, K. R. Richard, W. D. Glauz, and L. Elefteriadou. *NCHRP Report 505: Review of Truck Characteristics as Factors in Roadway Design.* Transportation Research Board of the National Academies, Washington, D.C., 2003.
9. Dowling, R., G. List, B. Yang, E. Witzke, and A. Flannery. *NCFRP Report 31: Incorporating Truck Analysis into the Highway Capacity Manual*. Transportation Research Board of the National Academies, Washington, D.C., 2014.
10. Butorac, M., J. Bonneson, K. Connolly, P. Ryus, B. Schroeder, K. Williams, Z. Wang, S. Ozkul, and J. Gluck. *Web-Only Document 256: Assessing Interactions Between Access Management Treatments and Multimodal Users.* Transportation Research Board, Washington, D.C., 2018.
11. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
12. Transportation Research Board. *Access Management: Manual and Application Guidelines—Linked.* Transportation Research Board, Washington, D.C., 2017.
13. Harwood, D. W., K. M. Bauer, I. B. Potts, D. J. Torbic, K. R. Richard, E. R. Kohlman Rabbani, E. Hauer, and L. Elefteriadou. *Safety Effectiveness of Intersection Left- and Right-Turn Lanes.* Report FHWA-RD-02-089. Federal Highway Administration, Washington, D.C., July 2002.
14. Solomon, D. H. *Accidents on Main Rural Highways Related to Speed, Driver, and Vehicle.* Bureau of Public Roads, Washington, D.C., 1964.
15. Stover, V. G., and F. J. Koepke, *Transportation and Land Development,* 2nd ed., Institute of Transportation Engineers, Washington, D.C., 2002.
16. Dowling, R., P. Ryus, B. Schroeder, M. Kyte, T. Creasey, N. Rouphail, A. Hajbabaie, and D. Rhoades. *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual.* Transportation Research Board, Washington, D.C., 2016.

CHAPTER 10

Right-Turn Lanes

Source: Photograph provided by the authors.

Description

A *right-turn lane* is an auxiliary lane provided to allow right-turning vehicles to conduct most of their deceleration and, if necessary, queue before making their turn. The technique of widening the right through lane to better accommodate right turns from driveways is also included as part of this group. A continuous right-turn lane should not be longer than one-quarter mile to avoid additional conflicts when there is both vehicular and bicycle traffic (*1*).

Tables 36 through 39 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

Chapter 19 in the HCM6 can be used to compare the change in delay as a result of installing right-turn lanes at signalized intersections (*4*), in cases where the right-turn lane is adequately sized to prevent queue spillback into the through lanes.

Simulation of right-turn delays at unsignalized (i.e., minor street stop-controlled) intersections on two-lane arterials found that right-turning-vehicle delay to through vehicles ranged from 0 to 6 seconds (*2*). The highest delay occurred with a high speed limit (55 mph), high through volumes (1,400 vehicles per hour), and high right-turn volumes (500 vehicles per hour). Delays on 4-lane arterials under the same conditions were in the range of 0–1 second. When pedestrians were present on the parallel crosswalk causing right-turning traffic to yield

Table 36. Multimodal operations and safety performance summary.

	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
Access Management Technique										
Install right-turn deceleration lanes where none exists.	↑ ●	↓ ●	↕ ●	↕ ●	↑ ●	↑ ●	↓ ●	↓ ●	↓ ●	↑ ●
Install continuous right-turn lane.	↑ ●	↓ ●	↓ ●	↕ ●	↑ ●	↕ ◐	↓ ◐	↓ ◐	↓ ◐	○
Widen right through lane to limit encroachment on adjacent lane from right-turn egress vehicles.	○	↕ ●	↓ ●	○	○	↑ ◐	↓ ◐	↕ ◐	○	○

Table 37. General trends associated with providing right-turn lanes.

Mode	Operations	Safety
	Motor vehicle free-flow and travel speeds increase by up to a few miles per hour. Speed increases are greater when only one through travel lane is available and with higher through traffic volumes, higher turning traffic volumes, and higher pedestrian volumes on the parallel crosswalk (*2*).	The motorized vehicle crash rate decreases (*3*). With continuous right-turn lanes, however, drivers exiting driveways may experience confusion about where approaching vehicles plan to turn. Widening the rightmost travel lane provides more space for large vehicles to turn onto the roadway without encroaching on the adjacent lane.
	Small negative effect on pedestrian LOS due to increased motor vehicle speeds (*4, 5*). At unsignalized intersections, crossing distance and pedestrian delay increase and pedestrian LOS may decrease (*4, 6*). The traffic signal cycle length may need to increase to accommodate longer pedestrian crossing distances, increasing pedestrian delay (*6*). Widening the rightmost travel lane increases the separation of traffic from the sidewalk, improving pedestrian LOS (*4, 5*).	May increase vehicle–pedestrian crash frequency if not channelized (*2*, *7*). Increases pedestrian exposure to traffic when crossing the major road, due to the widened roadway (*6*). Visually impaired pedestrians may experience difficulty crossing the driveway or minor street, as sound from through vehicles may mask the sound of a decelerating conflicting vehicle in the right-turn lane (*8*).
	Small reduction in bicycle delay (*9*). Higher vehicle speeds lower bicycle LOS (*4, 5*). Widening the rightmost travel lane improves bicycle LOS (*4, 5*).	Increases cross-street bicycle exposure to traffic due to widened cross-section (*6*). Requires consideration of vehicles' weaving maneuver into the right-turn lane (*6, 10*). A wider right-hand travel lane increases separation from motorized vehicles (*3*).
	Small increase in bus delay when a near-side bus stop is provided at a traffic signal (*9*). Without a near-side stop, bus benefits are similar to, but greater than, motor vehicles' benefits because buses accelerate more slowly to their running speed after stopping or slowing (*11*). At traffic signals, provides the potential for a queue jump or bypass (*12*). May constrain where bus stops can be located, require bus exemptions from right-turn-only requirements, or both (*12*).	Substantially increases conflicts between buses serving near-side stops and both right-turning and through vehicles (*9*). Conflicts with right-turning vehicles further increase when the bus stop is located prior to the stop bar or corner (*12*). Motor vehicle effects also apply to buses.
	Similar to motor vehicles, but with greater benefit for trucks, as they accelerate more slowly to their running speed after stopping or slowing (*13*). Improved truck LOS due to improved speeds (*14*).	Slightly reduces conflicts between trucks and other vehicles, with the effect greater with increasing turn-lane length (*9*). Motor vehicle effects also apply to trucks.

Table 38. Crash modification factors: Right-turn lanes.

Intersection Type	Traffic Volume: AADT (vehicles per day)	Crash Severity	Crash Modification Factor by Number of Approaches with Right-Turn Lanes: One Approach	Two Approaches
Urban or rural, minor road stop-controlled	Major: 1,500–40,600	All	0.86	0.74
	Minor: 25–26,000	Injury	0.77	—
	Unspecified	Injury	—	0.59
Urban or rural, signalized	Major: 7,200–55,100	All	0.96	0.92
	Minor: 550–8,400	Injury	0.91	—
	Unspecified	Injury	—	0.83

Note: Values apply to major street approaches at unsignalized intersections and any approach at signalized intersections. For signalized intersections with three or four approaches with right-turn lanes, the crash modification factor is the value for one approach raised to the third or fourth power, respectively. A dash indicates no crash modification factor provided for this combination of number of approaches, crash severity, and AADT.

There are intersection types associated with an unspecified AADT, as shown in the table (either minor road stop controlled, or signalized). The *Highway Safety Manual's* crash modification factors for injury crashes when one approach has a right-turn lane were developed by using data from sites with AADTs within the range given in the table. The studies used to develop crash modification factors in situations where two approaches had right-turn lanes did not specify the AADTs associated with the study sites.

Source: Highway Safety Manual, 1st ed., Tables 14-15 and 14-16 (*3*).

to them, through traffic experienced an additional 0–6 seconds of delay, with the highest delay occurring with high through volumes (1,200 vehicles per hour), high right-turn volumes (200 vehicles per hour), and high pedestrian volumes (200 pedestrians per hour).

Chapter 31, Section 4, in the HCM6 can be used to calculate a desired percentile back-of-queue for right-turn lanes at signalized intersections (*4*). A taper distance, allowing vehicles to maneuver from the through lane into the left-turn lane, and a deceleration distance need to be added to this storage length when determining the total left-turn lane length. Equation 16-2 in the *Access Management Manual*, Second ed. (*10*) can estimate the minimum storage distance for a right-turn lane. Workbook 12 that accompanies the linked version of the *Access Management: Manual and Application Guidelines* (*15*) is a spreadsheet tool for calculating the total right-turn lane length at signalized intersections.

Motor Vehicle Safety

The HSM provides crash modification factors related to installing right-turn lanes on the major street approaches to stop-controlled intersections and on any approach to a signalized intersection (*3*) (see Table 38 above).

Table 39. Crash rate ratios for various speed differentials on rural highways relative to no speed differential.

Speed Differential (mph)	Crash Rate Ratio Relative to no Speed Differential
0	1.0
–10	2.0
–20	6.5
–30	45
–35	180

Source: Solomon (*16*), Stover and Koepke (*17*).

Right-turn lanes that are too short to accommodate demand or that otherwise provide insufficient deceleration distance result in a greater speed differential between right-turning vehicles and through vehicles relative to the typical design differential of 10 mph (*1*). Table 39 (*16, 17*) gives crash rate ratios for various speed differentials on rural highways, relative to no speed differential. For example, the crash rate with a 10-mph speed differential is twice the crash rate with no speed differential.

Pedestrian Operations

Equations 18-32, 18-33, and 18-35 in the HCM6 (*4*) can determine the effect of motorized vehicle speeds and rightmost travel lane width on pedestrian link LOS. An increase in average traffic speed of 2 mph worsens the pedestrian link LOS score by 0.03 points (at 20 mph) to 0.08 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter. Increasing the rightmost lane width from 12 feet to 15 feet, assuming no parking or bicycle lane, and assuming a 6-foot curb-tight sidewalk, improves the pedestrian link LOS score by 0.10 points.

Equation 19-72 in the HCM6 (*4*) can determine the effect of intersection width on pedestrian intersection LOS. An increase of one lane of width worsens the pedestrian intersection LOS score by 0.13 (widening from 7 to 8 lanes, including turn lanes) to 0.23 points (2 to 3 lanes), with 1.00 point representing the range covered by one LOS letter.

Pedestrian Safety

Potts et al. (*7*) developed a model for predicting the frequency of vehicle–pedestrian crashes associated with a signalized intersection approach. The model includes an input variable that describes the right-turn design type (i.e., no turn lane, turn lane without channelizing island, turn lane with channelizing island). The model indicates that the addition of a right-turn lane (without channelization) increases the frequency of crashes relative to either no turn lane or a channelized right-turn lane. See the appendix for more details about the model.

Bicycle Operations

Equations 18-41, 18-42, and 18-44 in the HCM6 (*4*) can determine the effect of motorized vehicle speed and rightmost travel lane width on bicycle link LOS. An increase in average traffic speed of 2 mph worsens the bicycle link LOS score by 0.57 points (at 21 mph or less), 0.17 points (at 25 mph), 0.05 points (at 40 mph), and 0.03 points (at 50 mph), with 0.75 points representing the range covered by one LOS letter. Increasing the rightmost lane width from 12 feet to 15 feet, assuming no parking or bicycle lane, improves the bicycle link LOS score by 0.41 points.

Equation 19-80 in the HCM6 (*4*) can determine the effect of intersection width on bicycle intersection LOS. An increase in intersection width of 12 feet worsens the bicycle intersection LOS score by 0.18 points, with 1.00 point representing the range covered by one LOS letter.

A simulation study (*9*) found that right-turn deceleration lanes reduced bicycle delay at traffic signals in the range of 0.6 to 3.1 seconds, depending on the traffic signal cycle length and on truck, bicycle, and automobile volumes.

Bicycle Safety

Carter et al. (*18*) developed a model to predict a safety index for bicycle intersection. The index value would worsen by 0.47 rating points when a right-turn lane was added to a street where a bicycle lane is present, due to the interaction of right-turning vehicular traffic crossing over the path of through bicyclists. See the appendix for more details about this model.

Bus Operations

A simulation study (*9*) found that right-turn deceleration lanes increased bus delay at near-side stops at traffic signals in the range of 0.6 to 4.1 seconds, depending on the right-turn lane length, traffic signal cycle length, bus dwell time length, and vehicular volumes.

Bus Safety

A simulation study (*9*) found that conflicts between vehicles and buses stopping at a near-side stop located at the stop bar at a signalized intersection more than doubled for typical right-turn lane lengths. Because the intersections for which the simulation models were calibrated showed a linear relationship between different types of modeled vehicle–vehicle conflicts and their associated types of crashes, it was concluded that the crash rate would change proportionately to the conflict rate. Crashes involving public transit buses are rare; thus, it is not possible to develop crash modification factors or CMFs for buses from field data. However, based on the simulated conflicts, the following CMF was developed for crashes involving buses, where a right-turn lane was added at a bus stop:

$$\mathrm{CMF}_{\mathrm{bus}} = e^{(1.096 - 0.00084\,L_{RT})}$$

where L_{RT} is the right-turn lane length in feet and *e* represents exponential. The CMF is 2.75 for a 100-foot right-turn lane and 2.32 for a 300-foot right-turn lane.

Truck Operations

Section P in Exhibit 3 of *NCHRP Report 825* (*19*), derived from *NCFRP Report 31* (*14*), can be used to estimate the effect of improved truck free-flow and travel speeds on overall truck LOS. On a level street with a 35-mph free-flow speed, increasing average truck speeds from 25 to 26 mph results in a 1.3 percentage point increase in the truck LOS index, while increasing average truck speeds from 17.5 to 18.5 mph results in a 7.0 percentage point increase, with 10 percentage points representing the range covered by one LOS letter.

Truck Safety

A simulation study (*9*) found that the number of conflicts between vehicles and trucks was reduced when a left-turn lane was provided. Because the intersections for which the simulation models were calibrated showed a linear relationship between different types of modeled vehicle–vehicle conflicts and their associated types of crashes, it was concluded that the crash rate would change proportionately to the conflict rate. Based on the simulated conflicts, the following CMF was developed for crashes involving trucks when a right-turn lane was added at an intersection:

$$\mathrm{CMF}_{\mathrm{truck}} = e^{-0.00027\,L_{RT}}$$

The CMF is 0.97 for a 100-foot right-turn lane and 0.92 for a 300-foot right-turn lane.

Additional Information

- Chapter 11 in this guide.
- *Access Management Manual,* Second ed.: Chapter 16, Auxiliary Lanes, Sections 20.3.5 and 20.3.6.
- *Access Management Application Guidelines*: Chapter 22, Right-Turn Lanes.

References

1. Gluck, J., and M. Lorenz. *NCHRP Synthesis 404: State of the Practice in Highway Access Management*. Transportation Research Board of the National Academies, Washington, D.C., 2010.
2. Potts, I., J. Ringert, D. Harwood, and K. Bauer. Operational and Safety Effects of Right-Turn Deceleration Lanes on Urban and Suburban Arterials. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2023, 2007, pp. 52–62.
3. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
4. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
5. Dowling, R., D. Reinke, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, N. Rouphail, and J. Bonneson. *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
6. Dixon, K. K., R. D. Layton, M. Butorac, P. Ryus, J. L. Gattis, L. Brown, and D. Huntington. *Access Management Application Guidelines.* Transportation Research Board, Washington, D.C., 2016.
7. Potts, I. B., D. W. Harwood, K. M. Bauer, D. K. Gilmore, J. M. Hutton, D. J. Torbic, J. F. Ringert, A. Daleiden, and J. M. Barlow. *NCHRP Web-Only Document 208: Design Guidance for Channelized Right-Turn Lanes.* Transportation Research Board of the National Academies, Washington, D.C., July 2011.
8. Potts, I. B., D. W. Harwood, D. J. Torbic, D. K. Gilmore, J. F. Ringert, C. B. Tiesler, D. L. Harkey, and J. M. Barlow. *Synthesis on Right-Turn Deceleration Lanes on Urban and Suburban Arterials.* NCHRP Project 03-72. Transportation Research Board of the National Academies, Washington, D.C., Aug. 2006.
9. Butorac, M., J. Bonneson, K. Connolly, P. Ryus, B. Schroeder, K. Williams, Z. Wang, S. Ozkul, and J. Gluck. *Web-Only Document 256: Assessing Interactions Between Access Management Treatments and Multimodal Users.* Transportation Research Board, Washington, D.C., 2018.
10. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
11. Hemily, B., and R. D. King. *TCRP Synthesis 75: Uses of Higher Capacity Buses in Transit Service.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
12. Ryus, P., K. Laustsen, K. Blume, S. Beaird, and S. Langdon. *TCRP Report 183: A Guidebook on Transit-Supportive Roadway Strategies.* Transportation Research Board, Washington, D.C., 2016.
13. Harwood, D. W., D. J. Torbic, K. R. Richard, W. D. Glauz, and L. Elefteriadou. *NCHRP Report 505: Review of Truck Characteristics as Factors in Roadway Design.* Transportation Research Board of the National Academies, Washington, D.C., 2003.
14. Dowling, R., G. List, B. Yang, E. Witzke, and A. Flannery. *NCFRP Report 31: Incorporating Truck Analysis into the* Highway Capacity Manual. Transportation Research Board of the National Academies, Washington, D.C., 2014.
15. Transportation Research Board. *Access Management: Manual and Application Guidelines—Linked.* Transportation Research Board, Washington, D.C., 2017.
16. Solomon, D. H. *Accidents on Main Rural Highways Related to Speed, Driver, and Vehicle.* Bureau of Public Roads, Washington, D.C., 1964.
17. Stover, V. G., and F. J. Koepke, *Transportation and Land Development,* 2nd ed., Institute of Transportation Engineers, Washington, D.C., 2002.
18. Carter, D. L., W. W. Hunter, C. V. Zegeer, J. R. Stewart, and H. F. Huang. *Pedestrian and Bicyclist Intersection Safety Indices: Final Report.* Report FHWA-HRT-06-125. Federal Highway Administration, Washington, D.C., Nov. 2006.
19. Dowling, R., P. Ryus, B. Schroeder, M. Kyte, T. Creasey, N. Rouphail, A. Hajbabaie, and D. Rhoades. *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual.* Transportation Research Board, Washington, D.C., 2016.

CHAPTER 11

Driveway Channelization

Source: Photograph provided by the authors.

Description

Raised islands at the entrance to a driveway and medians within a driveway can be used to separate conflicting motorists, provide positive guidance to motorists, discourage prohibited turns, provide pedestrian refuge, reduce excessive pavement area, or facilitate a combination of these uses (*1*).

Tables 40 and 41 follow.

Quantitative Analysis Methods

NCHRP Report 659: Guide for the Geometric Design of Driveways (*1*) provides detailed guidance on designing driveway channelization.

Potts et al. (*3*) developed a model for predicting the frequency of vehicle–pedestrian crashes associated with a signalized intersection approach. The model indicates that a channelized right-turn lane at a traffic signal has a similar crash rate as the situation with no turn lane and a lower crash rate relative to an unchannelized right-turn lane. It is unknown whether the same relationships hold at unsignalized intersections. See the appendix for more details about the model.

Table 40. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships — Operations 🚗	🚶	🚲	🚌	🚚	Safety 🚗	🚶	🚲	🚌	🚚
Install channelizing island to move ingress merge point laterally away from roadway.	○	○	○	↓ ◐	○	↑ ◐	↕ ◐	○	○	↕ ◐
Move sidewalk–driveway crossing laterally away from roadway.	○	○	○	○	○	↑ ◐	↑ ◐	○	○	↑ ◐
Install 2 two-way driveways with limited turns in lieu of 1 full-access two-way driveway.	○	○	○	↓ ◐	○	↕ ◐	↔ ◐	↔ ●	○	↕ ◐
Install 2 two-way driveways with limited turns in lieu of 2 full-access two-way driveways.	○	○	○	○	○	↑ ◐	↑ ◐	↑ ●	○	↕ ◐
Install channelizing island to prevent left-turn driveway encroachment conflicts.	○	○	○	↓ ◐	○	↑ ◐	↕ ◐	○	○	↕ ◐
Install channelizing island to prevent right-turn ingress vehicles from returning to through lanes.	○	○	○	↓ ◐	○	↑ ◐	↕ ◐	○	○	↕ ◐
Install channelizing island to control the merge area of right-turn ingress vehicles.	○	○	○	↓ ◐	○	↕ ◐	↕ ◐	○	○	↕ ◐

Note: ↔ = unchanged performance.

Table 41. General trends associated with driveway channelization.

Mode	Operations	Safety
🚗	No direct effect. See Chapters 1 and 7.	Raised medians in the driveway help separate opposing traffic flows and prevent encroachments (*1*). Islands help separate right- and left-turning traffic entering driveways with multiple entry lanes. Setback pedestrian crossings allow drivers to exit traffic stream before having to stop for pedestrians (*1*, *2*). Flatter right-turn entry angle imposed by an island requires drivers to turn their heads at a sharper angle to observe approaching traffic and may encourage higher exiting speeds (*1*). Islands used to discourage prohibited turns are easy to violate if not accompanied by a sufficiently long median barrier (*1*). Islands that are too small do not stand out and may pose a traffic hazard (*1*).
🚶	No direct effect. See Chapters 1 and 7.	Sufficiently wide pedestrian refuges and islands provide pedestrian refuge, particularly on higher-volume driveways with multi-lane entries or exits (*1*). Islands can help discourage prohibited left-turn movements. See Chapters 1 and 7.
🚲	No direct effect. See Chapters 1 and 7.	Islands can help discourage prohibited left-turn movements. See Chapters 1 and 7.
🚌	Wider driveway widths at the point of intersection with the street will require that a midblock bus stop, if present, be located farther away from pedestrian facilities serving the site located along the driveway.	No documented effect beyond that generally observed for motor vehicle, pedestrian, and truck traffic.
🚚	No documented effect.	Channelization must accommodate the turning path of larger vehicles to avoid curb, pavement, and vehicle damage (*1*).

Additional Information

- Chapters 1, 2, 5, 7, 10, and 17 in this guide.
- *Access Management Manual,* Second ed.: Sections 13.7.6 and 20.2.6.
- *Access Management Application Guidelines*: Chapter 10, Driveway Design and Geometrics.
- *NCHRP Report 659: Guide for the Geometric Design of Driveways.*

References

1. Gattis, J. L., J. S. Gluck, J. M. Barlow, R. W. Eck, W. F. Hecker, and H. S. Levinson. *NCHRP Report 659: Guide for the Geometric Design of Driveways.* Transportation Research Board of the National Academies, Washington, D.C., 2010.
2. Layton, R., G. Hodgson, and K. Hunter-Zaworski. Pedestrian and Bicyclist Impacts of Access Management. *Proceedings of the Third National Access Management Conference*, Fort Lauderdale, Fla., 1998.
3. Potts, I. B., D. W. Harwood, K. M. Bauer, D. K. Gilmore, J. M. Hutton, D. J. Torbic, J. F. Ringert, A. Daleiden, and J. M. Barlow. *NCHRP Web-Only Document 208: Design Guidance for Channelized Right-Turn Lanes.* Transportation Research Board of the National Academies, Washington, D.C., July 2011.

CHAPTER 12

Alternative Intersections and Interchanges

Source: Photograph provided by Google Earth.

Description

Alternative intersections and interchanges reroute one or more turning movements, often left turns, from their normal location at a conventional four-leg intersection (*1*). A number of alternative intersection forms create secondary junctions to accommodate the rerouted movements (*1*, *2*). Alternative intersections are designed to reduce delay by reducing the number of signal phases required and improve safety by reducing the number of conflict points (*1*). Tables 42 through 44 follow.

Table 42 lists and describes a number of alternative intersection and interchange forms.

Quantitative Analysis Methods

Operations

Chapter 23 in the HCM6 (*1*) provides methods for analyzing the vehicular operations of diverging diamond interchanges, displaced left turns, median U-turns, restricted crossing U-turns, and conventional interchange areas. Chapters 19 and 20 in the HCM6 can be used to analyze conventional intersection forms with rerouted turning movements. When comparing intersection forms, the overall travel time by movement through the entire system of main and secondary junctions should be compared rather than simply control delay at the main intersection.

Table 42. Alternative intersection and interchange forms.

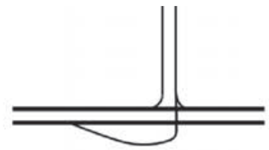
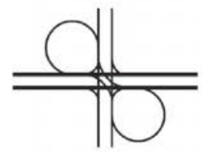
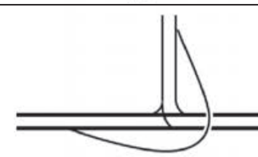
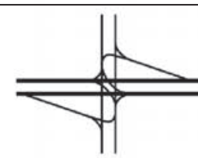
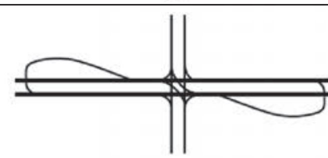
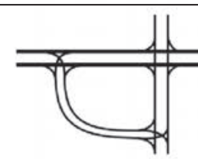
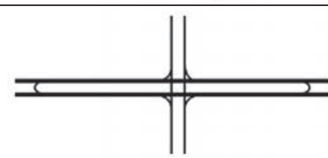
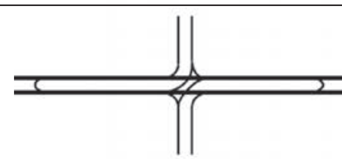
Intersection Type	Description	Diagram
Single Intersection Forms		
Indirect left turn (jughandle)	Major street left turns at a three-leg intersection exit right and form a fourth leg. Minor street left turns are prohibited (*2*).	
Jughandle with far-side ramp	Major street left turns pass through the intersection, use a loop ramp to merge onto the side street, and pass through the intersection again (*2*).	
Flyover	A major or a minor street left-turn movement is grade separated (*3*).	
Multiple Junction Forms		
Jughandle with near-side ramps	All major street turns exit prior to the intersection and make their turns at a secondary intersection with the cross street (*2*).	
Jughandle with median U-turn	Major street left turns pass through the intersection, exit right onto a jughandle ramp to make a U-turn, and then make a right turn at the intersection (*2*).	
Quadrant intersection	Left turns at the main intersection are redirected to connecting roadways via a series of right turns, left turns, or a mix of both (*2*).	
Median U-turn (Michigan U-turn)	Major street left turns pass through the intersection, make a U-turn at a directional median crossover, and return to the intersection to turn right. Minor street left turns make a right turn followed by a U-turn (*1*).	
Restricted crossing U-turn (superstreet)	Major street left turns and minor street left turns and through movements are redirected to directional U-turn crossovers on the major street beyond the intersection (*1*).	

Table 42. (Continued).

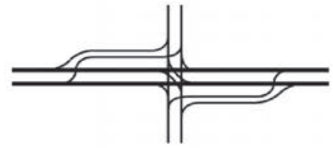
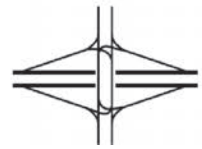
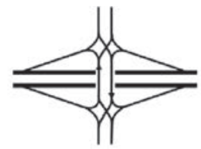
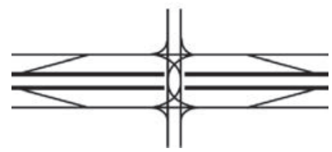
Intersection Type	Description	Diagram
Displaced left turn (continuous flow intersection)	Left turns on one or both streets are crossed over to the far side of opposing traffic prior to reaching the main intersection (*1*).	
Grade-separated intersection	The major street goes under or over the minor street. The minor street is accessed via ramps from the major street (*3*).	
Interchange Forms		
Diverging diamond interchange	Through traffic on the arterial is crossed over to the opposite side prior to the interchange and crossed back after the interchange, allowing free-flowing turning movements (*1*).	
Freeway frontage roads	Traffic exiting the freeway merges onto a one-way frontage road before turning onto the crossroad. Traffic to the freeway uses a left-hand ramp from the frontage road (*3*).	

Table 43. Multimodal operations and safety performance summary.

	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
Access Management Technique	🚗	🚶	🚲	🚌	🚚	🚗	🚶	🚲	🚌	🚚
Implement indirect left turns at existing intersection.	↕ ●	↓ ◐	↕ ◐	○	○	↑ ◐	○	↓ ◐	○	○
Redirect left turns via connecting roadways.	↕ ●	○	○	○	○	○	○	○	○	○
Redirect left turns via flyover.	↑ ●	↓ ◐	↓ ◐	○	○	↑ ◐	○	↓ ◐	○	○
Redirect left turns via U-turns.	↕ ●	↓ ◐	↕ ◐	○	↓ ◐	↑ ●	○	○	○	○
Redirect left turns by displacing travel lanes.	↑ ●	○	○	↕ ◐	○	○	↓ ◐	↕ ◐	○	○
Build interchange at activity center or major intersection.	↑ ●	↓ ◐	↓ ◐	○	○	↑ ◐	○	↓ ◐	○	○
Modify freeway ramps to improve access.	↑ ◐	○	○	○	○	○	○	○	○	○
Build freeway frontage roads.	↕ ◐	○	○	○	○	○	○	○	○	○

Table 44. General trends associated with alternative intersections and interchanges.

Mode	Operations	Safety
	Typically increase capacity and reduce major street vehicular delay at the main intersection (*1*). May increase overall travel time for rerouted turning movements (*1*). Clear signing is required to indicate the required lane positioning for rerouted turning movements, as well as to prevent wrong-way movements (*4–8*). Multiple junction forms must consider the interactions of the main and secondary junctions (*2*). Restricted crossing U-turns allow separate progression bands for each direction (*2*).	Typically decrease the total number of conflict points, although not necessarily the conflicting volume (*4–8*). Quantitative safety information not available for many alternative intersection forms.
	Typically allow shorter traffic signal cycle lengths and thus reduced pedestrian delay for a given crossing stage (*4–8*). Some intersection forms require multiple-stage pedestrian crossings (*6*, *8*). Signalized U-turn crossovers offer the potential for signalized midblock pedestrian crossings without affecting traffic progression (*7*).	Often decrease the total number of vehicle–pedestrian conflict points (*4–7*). Depending on intersection type, traffic at crossings may approach from an unexpected direction (*5*). Intersection forms with channelized right turns require special attention to the pedestrian crossings of the right turns (*6*). See Chapter 11.
	Typically allow shorter traffic signal cycle lengths and a greater percentage of green time for movements, thus reducing delay (*7*). Can be traversed in the same ways as conventional intersections—as a vehicle, as a pedestrian, or by making a two-stage left turn (*6*). Restricted crossing U-turns pose a challenge for bicyclists affected by rerouted movements (*8*).	Typically decrease the total number of vehicle–bicycle conflict points (*4–8*). Ramp and channelized right-turn merge and diverge points require special attention (*6*).
	Similar to motor vehicles and trucks. Median U-turns can accommodate a bus or rail transit guideway in the roadway median (*7*). Can be challenging to place bus stops at displaced left turns (*6*). Center island of diverging diamond interchanges can be used for bus stops serving transfers between arterial and freeway-based transit routes (*5*).	No documented effect beyond that generally observed for motor vehicle and pedestrian traffic.
	Intersection forms requiring U-turns may need a loon (widened pavement area on the edge of the roadway) to accommodate larger vehicles' turning radii (*7*, *8*).	No documented effect beyond that generally observed for motor vehicle traffic.

Note: Given the range of alternative intersection forms and the availability of information specific to each type (*2–8*), only general trends and the most important aspects of selected alternative intersection forms are in the table.

Chapter 23 in the HCM6 provides a measure—*experienced travel time*—for performing such a comparison (*1*).

No methods have been developed yet for assessing pedestrian or bicycle performance at alternative intersections. Estimates of vehicular speed can be used as starting points for estimating bus and truck speeds.

Safety

Because of the relative rarity and in some cases relative newness of alternative intersection and interchange forms, few quantitative safety studies have been performed. Some of the studies that have been performed are simple before-and-after studies that did not correct for potential biases such as traffic volume changes and regression to the mean (*5*). Several FHWA publications (*4–8*) summarize available knowledge about alternative intersection and interchange safety.

An FHWA synthesis of 25 studies of median U-turn intersections (*9*) found the following reductions in crash rates at Michigan U-turns relative to conventional signalized intersections:

- Corridor-wide, all crash severities: 14%
- Intersections, all crash severities: 16%
- Intersections, injury crashes: 30%

Additional Information

- Chapters 1, 2, and 14 in this guide.
- *Access Management Manual,* Second ed.: Sections 20.2.8 and 20.5.
- FHWA alternative intersection informational reports and guides (*4–8*).

References

1. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
2. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
3. Gluck, J., H. S. Levinson, and V. Stover. *NCHRP Report 420: Impacts of Access Management Techniques.* Transportation Research Board of the National Academies, Washington, D.C., 1999.
4. Hughes, W., R. Jagannathan, D. Sengupta, and J. Hummer. *Alternative Intersections/Interchanges: Informational Report.* Report FHWA-HRT-09-060. Federal Highway Administration, Washington, D.C., April 2010.
5. Schroeder, B., C. Cunningham, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Diverging Diamond Interchange Informational Guide.* Report FHWA-SA-14-067. Federal Highway Administration, Washington, D.C., Aug. 2014.
6. Steyn, H., Z. Bugg, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Displaced Left Turn Informational Guide.* Report FHWA-SA-14-068. Federal Highway Administration, Washington, D.C., Aug. 2014.
7. Reid, J., L. Sutherland, B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Median U-Turn Informational Guide.* Report FHWA-SA-14-069. Federal Highway Administration, Washington, D.C., Aug. 2014.
8. Hummer, J., B. Ray, A. Daleiden, P. Jenior, and J. Knudsen. *Restricted Crossing U-Turn Informational Guide.* Report FHWA-SA-14-070. Federal Highway Administration, Washington, D.C., Aug. 2014.
9. Jagannathan, R. *Synthesis of the Median U-Turn Intersection Treatment, Safety, and Operational Benefits.* Publication FHWA-HRT-07-033. Federal Highway Administration, Washington, D.C., 2007.

CHAPTER 13

Parking and Stopping Restrictions

Source: Photograph provided by the authors.

Description

On-street parking is eliminated and off-street parking is substituted. Curbside stopping and loading activity occur off-street or during off-peak periods.

Tables 45 and 46 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

Exhibit 18-11 in the HCM6 indicates that roadway free-flow speeds increase by 0.03 mph for each 1% reduction in the percentage of street length where on-street parking is allowed (*2*). Thus, eliminating on-street parking increases the free-flow speed by up to 3 mph and average travel speeds by a little less than the increase in the free-flow speed. In most cases, the speed increase will be lower, because right-turn lanes, driveways, and unsignalized intersections between traffic signals will reduce the street length where parking is not restricted and where parking is frequently restricted near driveways.

Motor Vehicle Safety

Table 13-50 in the HSM provides the following crash modification factors associated with prohibiting on-street parking (*3*). They are

Table 45. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships: Operations					Safety				
	Car	Pedestrian	Bicycle	Bus	Truck	Car	Pedestrian	Bicycle	Bus	Truck
Replace curb parking with off-street parking.	↑ ●	↓ ●	↑ ●	↑ ◐	○	↑ ●	↑ ◐	↑ ●	○	○
Implement curbside loading controls.	↑ ◐	○	↑ ◐	↑ ◐	○	○	○	↑ ◐	○	○

- Arterial (64-ft wide with 30,000 AADT): 0.58 (all crash severities), and
- Arterial with 30,000–40,000 AADT: 0.78 (injury crashes), 0.72 (non-injury crashes).

Pedestrian Operations

Equations 18-32, 18-33, and 18-35 in the HCM6 (*2*) can determine the effect of prohibiting on-street parking on pedestrian link LOS. The removal of the barrier effect created by the parking reduces the pedestrian LOS score by 0.12–0.86 points, depending on how much parking was previously available and occupied, assuming 6-foot sidewalks, no landscape buffer, and standard lane widths. Increasing average traffic speeds by 2 mph worsens the pedestrian link LOS score by 0.03 points (at 20 mph) to 0.08 points (at 50 mph). The range covered by one LOS letter is 0.75 points.

Bicycle Operations

Equations 18-41, 18-42, and 18-44 in the HCM6 (*2*) can determine the effect of parking prohibitions on bicycle link LOS. The removal of the discomfort caused by riding between traffic

Table 46. General trends associated with removing on-street parking.

Mode	Operations	Safety
	Motor vehicle free-flow and travel speeds increase by up to a few miles per hour, depending on the proportion of the street length where on-street parking was previously available (*1, 2*).	Reduces the vehicular crash rate (*3*).
	Eliminating on-street parking will decrease pedestrian LOS, because parked cars serve as a barrier between traffic and pedestrians on the sidewalk and because motor vehicle speeds increase (*2, 4*).	Improves the visibility of pedestrians for drivers turning into a driveway (*1*).
	Eliminating on-street parking substantially improves bicycle LOS (*2, 4*). This improvement is slightly offset by the small increase in motor vehicle speeds (*2, 4*).	Eliminates the potential for "dooring" crashes. Improves the visibility for bicyclists crossing or who are about to cross a driveway (*5*). Improves interaction between bicycles and adjacent traffic (*3*).
	Similar to motor vehicles. Space previously used for parking can be repurposed as a curb extension at bus stops, providing space for passenger amenities and reducing bus delays leaving stops (but with potential impacts to motor vehicle and bicycle traffic) (*6*).	No documented effect beyond that generally observed for motor vehicle and pedestrian traffic.
	No documented effect beyond that generally observed for motor vehicle traffic.	No documented effect beyond that generally observed for motor vehicle traffic.

and a row of parked cars improves the bicycle LOS score by 0.38 to 2.00 points, depending on how much parking was previously available and occupied. In addition, the space previously used for parking becomes available for bicyclists to separate themselves from moving traffic and to maintain their line of travel (or can be explicitly striped as a bicycle lane), resulting in a greater improvement of the bicycle LOS score of 1.92 points, assuming an 8-foot parking lane. An increase in average traffic speed of 2 mph worsens the bicycle LOS score by 0.57 points (at 21 mph or less), 0.17 points (at 25 mph), 0.05 points (at 40 mph), and 0.03 points (at 50 mph). The range covered by one LOS letter is 0.75 points.

Bicycle Safety

Carter et al. (*7*) developed a model to predict a safety index for bicycle intersection; index values for all bicycle movements at an intersection improve by 0.2 rating points with the elimination of on-street parking on the intersection approach. See the appendix for more details about this model.

Additional Information

- Chapter 15 in this guide.
- *Access Management Manual,* Second ed.: Section 10.5.7.

References

1. Texas Transportation Institute; Kittelson & Associates, Inc.; and Purdue University. *Predicting the Performance of Automobile Traffic on Urban Streets.* Final report. NCHRP Project 03-79. Transportation Research Board of the National Academies, Washington, D.C., Jan. 2008.
2. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
3. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
4. Dowling, R., D. Reinke, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, N. Rouphail, and J. Bonneson. *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
5. Gattis, J. L., J. S. Gluck, J. M. Barlow, R. W. Eck, W. F. Hecker, and H. S. Levinson. *NCHRP Report 659: Guide for the Geometric Design of Driveways.* Transportation Research Board of the National Academies, Washington, D.C., 2010.
6. Ryus, P., K. Laustsen, K. Blume, S. B., and S. Langdon. *TCRP Report 183: A Guidebook on Transit-Supportive Roadway Strategies.* Transportation Research Board, Washington, D.C., 2016.
7. Carter, D. L., W. W. Hunter, C. V. Zegeer, J. R. Stewart, and H. F. Huang. *Pedestrian and Bicyclist Intersection Safety Indices: Final Report.* Report FHWA-HRT-06-125. Federal Highway Administration, Washington, D.C., Nov. 2006.

CHAPTER 14

Roundabouts

Source: Photograph provided by Washington State DOT.

Description

A *modern roundabout* is a form of circular intersection in which traffic circulates counter-clockwise around a central island and entering traffic yields to circulating traffic (*1*). This technique is intended to reduce the delay and crashes associated with signalized intersections.

Tables 47 through 50 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

Methods in Chapter 22 in the HCM6 can be used to estimate delay, capacity, queues, and other performance measures for motor vehicles at roundabouts (*5*). Those performance values can be compared with performance values for other intersection forms by using the appropriate HCM6 chapters for those intersections.

Motor Vehicle Safety

The table from the HSM, displayed on Page 68, provides crash modification factors related to converting a signalized intersection into a modern roundabout (*2*).

The HSM also provides table data on crash modification factors related to converting a minor road, stop-controlled intersection into a modern roundabout (*2*).

Table 47. Multimodal operations and safety performance summary.

	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
Access Management Technique										
Install roundabout in lieu of traffic signal.	↕ ●	↕ ●	↕ ●	↕ ◐	↕ ◐	↑ ●	↕ ◐	↕ ◐	○	○

Table 48. General trends associated with installing a roundabout in lieu of a traffic signal.

Mode	Operations	Safety
	For identical traffic volumes, roundabouts operating within their capacity will generally produce lower delays (*1*). Facilitates U-turns (*1*). Random departure pattern at exits breaks up traffic progression and may reduce available gaps for midblock turns (*1*).	The motorized vehicle crash rate is lower, and the injury crash rate is substantially lower (*2*).
	Depending on driver-yielding behavior, pedestrians may experience reduced delay relative to a traffic signal-controlled intersection (*3*). Longer travel distance through a roundabout than at a conventional signalized intersection.	Fewer vehicle–pedestrian conflict points, shorter crossing distances per crossing, and lower vehicle speeds improve pedestrian safety (*1*). Visually impaired pedestrians may experience difficulty crossing roundabout approaches, as circulating traffic may mask the sound of exiting traffic (*1*).
	Longer travel distance through a roundabout than at a conventional signalized intersection, but potentially easier left-turning maneuvers.	Fewer vehicle–bicycle conflict points and vehicle speeds similar to bicycle speeds improve safety, but separate bicycle facilities may be required at higher vehicular and bicycle volumes (*1*). Multi-lane roundabouts can be challenging for bicyclists (*1*).
	Precludes ability to provide a far-side stop where a single-lane exit is used unless a bus pullout is provided (*1*). Bus pullouts introduce delay for buses re-entering the roadway (*4*).	No documented effect beyond that generally observed for motor vehicle and pedestrian traffic.
	Circulatory roadway and truck apron width should accommodate the design vehicle (*1*).	No documented effect beyond that generally observed for motor vehicle traffic.

Table 49. Crash modification factors related to conversion of a signalized intersection into a roundabout.

Intersection Type	Crash Severity	Crash Modification Factor
Urban, 1 or 2 lanes	All	0.99
	Injury	0.40
Suburban, 2 lanes	All	0.33
All settings, 1 or 2 lanes	All	0.52
	Injury	0.22

Source: *Highway Safety Manual,* 1st ed., Table 14-3 (*2*).

Table 50. Crash modification factors related to conversion of a minor road, stop-controlled intersection into a roundabout.

Intersection Type	Crash Severity	Crash Modification Factor
All settings, 1 or 2 lanes	All Injury	0.56 0.18
Rural, 1 lane	All Injury	0.29 0.13
Urban, 1 or 2 lanes	All Injury	0.71 0.19
Urban, 1 lane	All Injury	0.61 0.22
Urban, 2 lanes	All	0.88
Suburban, 1 or 2 lanes	All Injury	0.68 0.29
Suburban, 1 lane	All Injury	0.22 0.22
Suburban, 2 lanes	All Injury	0.81 0.32

Source: Highway Safety Manual, 1st ed., Table 14-4 (*2*).

Pedestrian Operations

The pedestrian method in Chapter 2 in the HCM6 can be used to evaluate pedestrian delay when crossing roundabout approaches. The use of a local value for driver-yielding behavior will produce the accurate results (*5*).

Bicycle Operations

Bicycles traveling through a roundabout as vehicles (i.e., using the circulatory roadway) will experience control delays similar to that of motorized vehicles. Bicycles traveling through the roundabout as pedestrians, or using a shared-use path around the exterior of the roundabout, will experience control delays similar to pedestrians (*5*).

Additional Information

- Chapters 1 and 2 in this guide.
- *Access Management Manual,* Second ed.: Section 20.5.3.
- *Access Management Application Guidelines*: Chapter 14, Roundabout Access Spacing.

References

1. Rodegerdts, L., J. Bansen, C. Tiesler, J. Knudsen, E. Myers, M. Johnson, M. Moule, B. Persaud, C. Lyon, S. Hallmark, H. Isebrands, R. B. Crown, B. Guichet, and A. O'Brien. *NCHRP Report 672: Roundabouts: An Informational Guide,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2010.
2. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
3. Dixon, K. K., R. D. Layton, M. Butorac, P. Ryus, J. L. Gattis, L. Brown, and D. Huntington. *Access Management Application Guidelines.* Transportation Research Board, Washington, D.C., 2016.
4. Kittelson & Associates, Inc.; Parsons Brinckerhoff; KFH Group, Inc.; Texas A&M Transportation Institute; and Arup. *TCRP Report 165: Transit Capacity and Quality of Service Manual,* 3rd ed. Transportation Research Board of the National Academies, Washington, D.C., 2013.
5. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.

CHAPTER 15

Driveway Sight Distance

Source: Photograph provided by the authors.

Description

Driveway sight distance considers (*1*):

- **Stopping sight distance,** the sight distance required for a driver to perceive and react to a hazard, and then brake to a stop prior to the hazard;
- **Intersection sight distance,** the sight distance required for drivers exiting an access connection or making a left turn into an access connection to safely make the maneuver; and
- **Decision sight distance,** the sight distance required for drivers to ascertain and safely respond to an unexpected, difficult, or unfamiliar situation, such as finding the access connection serving a business they have not previously visited.

Tables 51 and 52 follow.

Quantitative Analysis Methods

Motor Vehicle Safety

AASHTO's Green Book (*5*) provides guidance on selecting appropriate values for stopping, intersection, and design sight distance.

Pedestrian Operations

Equations 18-32 and 18-33 in the HCM6 (*3*) can determine the effect of parking reduction on pedestrian link LOS. A decrease in the curb length with occupied parking of 10 percentage

Table 51. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships: Operations					Safety				
										
Regulate minimum sight distance.	↑ ◐	○	○	○	○	↑ ◐	↑ ◐	↑ ◐	○	○
Improve driveway sight distance.	↑ ◐	○	○	↕ ◐	○	↑ ◐	↑ ◐	↑ ◐	○	○
Restrict on-street parking next to driveways.	↑ ◐	↓ ●	↑ ●	○	○	↑ ◐	↑ ◐	↑ ◐	○	○
Install visual cues for driveway.	↑ ◐	○	○	○	○	↑ ◐	↑ ◐	↑ ◐	○	○
Optimize sight distance in permit authorization stage.	↑ ◐	○	○	○	○	↑ ◐	↑ ◐	↑ ◐	○	○

points—with 6-foot sidewalks, no landscape buffer, and standard lane widths—reduces the pedestrian LOS score by 0.06–0.12 points, with 0.75 points representing the range covered by one LOS letter.

Bicycle Operations

Equations 18-41 and 18-42 in the HCM6 (*3*) can determine the effect of reduced parking on bicycle link LOS. A decrease in the curb length with occupied parking of 10 percentage points improves the bicycle LOS score by 0.02 to 0.38 points, with 0.75 points representing the range covered by one LOS letter, with lower reductions at higher percentages of occupied parking.

Table 52. General trends associated with improving driveway sight distance.

Mode	Operations	Safety
	Improved decision sight distance and driveway conspicuity may result in reduced motorist hesitancy.	Intersection sight distance provides sufficient distance for drivers to see and react appropriately to potential conflicts (*2*). Improved decision sight distance and driveway conspicuity may result in fewer erratic maneuvers by drivers.
	Removing some on-street parking to improve intersection sight distance slightly decreases pedestrian LOS because parked cars serve as a barrier between traffic and pedestrians on the sidewalk (*3, 4*).	Provides sufficient distance for drivers to see and react appropriately to pedestrians crossing or about to cross the driveway (*2*).
	Removing some on-street parking to improve intersection sight distance slightly improves bicycle LOS (*3, 4*).	Provides sufficient distance for drivers to see and react appropriately to bicyclists crossing or about to cross the driveway (*2*).
	Improving intersection sight distance may require relocating an adjacent bus stop (*1*).	No documented effect beyond that generally observed for motor vehicle and pedestrian traffic.
	No documented effect beyond that generally observed for motor vehicle traffic.	No documented effect beyond that generally observed for motor vehicle traffic.

Additional Information

- Chapters 13, 16, and 17 in this guide.
- *Access Management Manual,* Second ed.: Sections 13.4.2 and 13.4.3.
- *Access Management Application Guidelines*: Chapter 10, Driveway Design and Geometrics.

References

1. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
2. Gattis, J. L., J. S. Gluck, J. M. Barlow, R. W. Eck, W. F. Hecker, and H. S. Levinson. *NCHRP Report 659: Guide for the Geometric Design of Driveways.* Transportation Research Board of the National Academies, Washington, D.C., 2010.
3. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
4. Dowling, R., D. Reinke, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, N. Rouphail, and J. Bonneson. *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board of the National Academies, Washington, D.C., 2008.
5. American Association of State Highway and Transportation Officials. *A Policy on Geometric Design of Highways and Streets,* 6th ed. American Association of State Highway and Transportation Officials. Washington, D.C., 2011.

CHAPTER 16

One-Way Driveways

Source: Photograph provided by the authors.

Description

A *driveway designed and signed to allow either entering or exiting movements, but not both*. One-way driveways may be used to support site-circulation needs (e.g., drive-through lanes or fuel pumps), to provide access at a location where only certain movements are suitable, or to support right-in, right-out access to a site (*1*).

Tables 53 and 54 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

Methods in the HCM6 can be used to compare the operations of 2 one-way driveways with that of 1 or 2 two-way driveways (*2*).

Equation 18-3 and Exhibit 18-11 in the HCM6 give the reduction in roadway free-flow speed due to access point density (*2*). This reduction (in mph) equals $-0.078\ D_a/N_{th}$, where D_a is the number of access points per mile (considering both sides of the roadway) and N_{th} is the number of through lanes in the direction of travel. The resulting increase in average travel speed will be slightly lower, as discussed in the appendix. For an individual site, using 2 one-way driveways in lieu of 1 two-way driveway will reduce average travel speeds by a negligible 0.04 mph (4-lane roads) or 0.07 mph (2-lane roads). However, if most accesses along a section of roadway have been designed for one-way operation, the cumulative effect will be more significant.

Table 53. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships: Operations					Safety				
										
Install 2 one-way driveways in lieu of 1 two-way driveway.	↕ ●	○	↕ ●	↓ ◐	○	↕ ◐	↕ ◐	↕ ◐	○	○
Install 2 one-way driveways in lieu of 2 two-way driveways.	↑ ●	○	○	○	○	↑ ◐	↕ ◐	↕ ◐	○	○
Provide reversible operation of driveway.	○	○	○	○	○	○	○	○	○	○
Require two-way driveway operation where internal circulation not available.	○	○	○	○	○	○	○	○	○	○

Motor Vehicle Safety

Section 13.8 in the *Access Management Manual* (*3*) provides guidance on designing one-way driveways to encourage proper driver use.

Bicycle Operations

Equations 18-41 and 18-44 in the HCM6 (*2*) can determine the effect of motorized vehicle speeds on bicycle LOS, while Equations 18-46 and 18-47 can determine the effect of unsignalized access spacing on bicycle LOS. For an individual site on a suburban arterial, using 2 one-way

Table 54. General trends associated with installing one-way driveways.

Mode	Operations	Safety
	In selected situations (e.g., drive-through lanes or gas stations) can help support internal site circulation (*1*). If used frequently along a roadway, installing 2 one-way driveways in lieu of 1 two-way driveway will reduce free flow and travel speeds due to the increased number of access points drivers must monitor (*2*).	Requires careful attention to geometric design and signing to minimize intentional and unintentional wrong-way use of driveways (*3*). Skewed exits require drivers to turn their head sharply to view potential conflicts (*4*). Skewed entries may encourage higher-speed right-turn maneuvers but may also discourage prohibited left-turn maneuvers.
	No documented effect.	Skewed exits require drivers to turn their head sharply to view potential conflicts (*4*). Skewed entries may encourage higher-speed right-turn maneuvers.
	Bicycle LOS decreases when the unsignalized access point frequency on the right side of the road exceeds 20 points per mile. This decrease is partially (or wholly, at traffic speeds less than 25–30 mph) offset by the decrease in motor vehicle speeds, which positively affects bicycle LOS (*2, 5*).	Skewed exits require drivers to turn their head sharply to view potential conflicts (*4*). Skewed entries may encourage higher-speed right-turn maneuvers.
	Similar effects as for motor vehicles. Closely spaced entry and exit driveways may preclude the ability to provide a midblock bus stop at that location.	No documented effect beyond that generally observed for motor vehicle traffic.
	No documented effect beyond that generally observed for motor vehicle traffic.	No documented effect beyond that generally observed for motor vehicle traffic.

driveways in lieu of 1 two-way driveway will reduce the bicycle LOS by no more than 0.01 point, where 0.75 points represents the range covered by one LOS letter. If most accesses along a section of roadway have been designed for one-way operation, the cumulative effect will be more significant.

Additional Information

- Chapters 1, 11, 15, and 17 in this guide.
- *Access Management Manual,* Second ed.: Section 13.8.
- *Access Management Application Guidelines*: Section 10.5.4.
- *NCHRP Report 659: Guide for the Geometric Design of Driveways*

References

1. Dixon, K. K., R. D. Layton, M. Butorac, P. Ryus, J. L. Gattis, L. Brown, and D. Huntington. *Access Management Application Guidelines.* Transportation Research Board, Washington, D.C., 2016.
2. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
3. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
4. Gattis, J. L., J. S. Gluck, J. M. Barlow, R. W. Eck, W. F. Hecker, and H. S. Levinson. *NCHRP Report 659: Guide for the Geometric Design of Driveways.* Transportation Research Board of the National Academies, Washington, D.C., 2010.
5. Dowling, R., D. Reinke, A. Flannery, P. Ryus, M. Vandehey, T. Petritsch, B. Landis, N. Rouphail, and J. Bonneson. *NCHRP Report 616: Multimodal Level of Service Analysis for Urban Streets.* Transportation Research Board of the National Academies, Washington, D.C., 2008.

CHAPTER 17

Driveway Width

Source: Photograph provided by the authors.

Description

The driveway throat width, effective curb return radius, and angle of intersection with the roadway act in combination to provide safe and efficient operations at the point where a driveway intersects a roadway (*1*). *Throat width* is the normal driveway width, not including any widening associated with a radius or flare (*2*). *Effective curb return radius* considers both the physical construction of the curb and other roadway elements (e.g., a bicycle lane) that affect how vehicles make turning maneuvers (*1*).

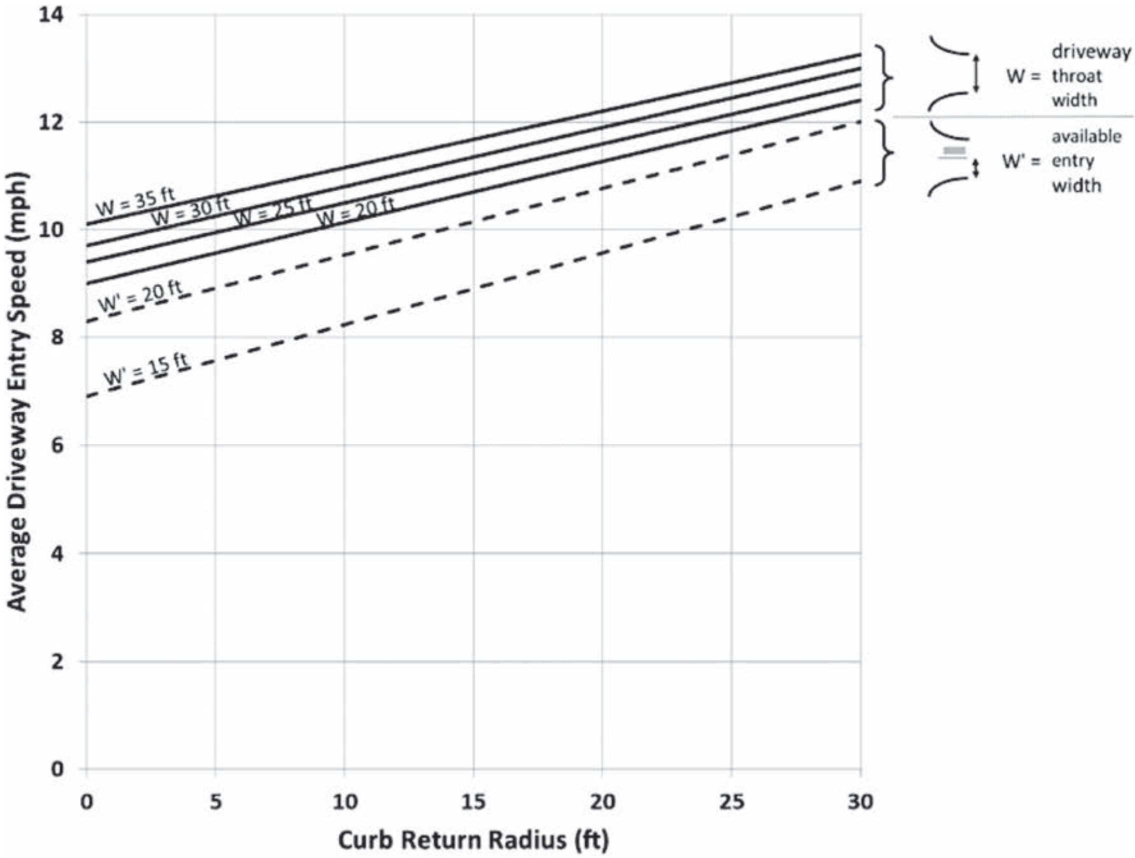
Figure 1 and Tables 55 through 57 follow.

Quantitative Analysis Methods

NCHRP Report 659 (*2*) provides guidance on throat widths, curb return radii, and driveway skew angles that, in combination, help provide safe and efficient driveway operations. Methods in the HCM6 (*4*) can be used to evaluate the capacity and queue storage benefits of adding one or more lanes to the driveway exit.

A study in South Carolina (*5*) found that increasing the driveway width increases the crash rate at the driveway. The same study found that increasing the number of driveway entry lanes from 1 to 2 decreases the crash rate.

An FHWA synthesis from the 1980s developed the following relationships between driveway width, curb return radius, and vehicle speed (*1*, *6*), as shown in Figure 1.



Source: *Access Management Manual*, Second ed. (*1*), adapted from Hagenaur et al. (*6*).

Figure 1. Relationships between driveway throat width, curb return radius, and average vehicle speed.

Table 55. Multimodal operations and safety performance summary.

	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
Access Management Technique	Car	Pedestrian	Bicycle	Bus	Truck	Car	Pedestrian	Bicycle	Bus	Truck
Regulate maximum driveway width.	○	↑ ◐	○	○	○	↑ ◐	↑ ◐	↑ ◐	○	○
Widen driveway to improve storage.	↑ ●	○	○	○	○	○	↕ ◐	↕ ◐	○	○
Install additional driveway exit lane.	↑ ●	○	○	○	○	○	↓ ◐	↓ ◐	○	○
Increase driveway's effective approach width.	↑ ◐	○	○	○	↑ ◐	↑ ◐	↕ ◐	↕ ◐	○	↑ ◐
Install barrier to prevent uncontrolled access along property frontage.	○	↑ ●	○	○	○	↑ ◐	○	○	○	○

Table 56. General trends associated with inadequate throat widths or curb radii.

Mode	Operations	Safety
	Vehicles may need to turn more slowly than normal into the driveway, which increases the potential for delaying following vehicles (*2*). At higher-volume driveways, the number of exiting lanes may provide insufficient capacity to serve demand (*2*).	Increases the chances of vehicles encroaching on the curb, sidewalk, or exiting driveway lane (*2*). Larger entering vehicles may need to wait in the street until exiting vehicles have cleared (*1*).
	No documented effect.	Increases the chances of vehicles encroaching on the curb or sidewalk (*2*).
	The existence of a bicycle lane provides a larger effective curb radius and may allow a smaller physical curb radius, although some agencies prefer not to do so in case the roadway cross-section is repurposed in the future, leaving an inadequate radius (*2*).	Larger entering vehicles may need to wait in the street until exiting vehicles have cleared (*1*), which may force bicycles to go around them or wait.
	No documented effect.	No documented effect beyond that generally observed for motor vehicle traffic.
	Trucks and other large vehicles (e.g., recreational vehicles) may not be able to enter until exiting vehicles have cleared the driveway (*1*).	Trucks may need to encroach on the curb, sidewalk, or opposing driveway lane when entering or exiting (*2*). Larger entering vehicles may need to wait in the street until exiting vehicles have cleared (*1*).

Table 57. General trends associated with excessively wide driveways.

Mode	Operations	Safety
	No documented effect.	Vehicles enter and exit at random locations and are more likely to cross paths (*2*).
	Provides an opportunity to install a median in the driveway that can act as a pedestrian refuge (*3*), reducing pedestrian delay, and can help orient pedestrians with impaired vision (*2*). Providing a barrier between the sidewalk and roadway to control access would also improve pedestrian LOS (*2*).	Increases the time and distance that pedestrians are exposed to conflicting traffic (*2*). May be more likely to seriously disorient a pedestrian with impaired vision (*2*). Increases average vehicle speeds entering the driveway (*1*).
	No documented effect.	Increases the time and distance that bicyclists are exposed to conflicting traffic (*2*). Increases average vehicle speeds entering the driveway (*1*).
	No documented effect.	No documented effect beyond that generally observed for motor vehicle traffic.
	No documented effect.	No documented effect beyond that generally observed for motor vehicle traffic.

Additional Information

- Chapters 11, 15, and 19 in this guide.
- *Access Management Manual,* Second ed.: Section 13.7.
- *Access Management Application Guidelines*: Chapter 10, Driveway Design and Geometrics.
- *NCHRP Report 659: Guide for the Geometric Design of Driveways.*

References

1. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
2. Gattis, J. L., J. S. Gluck, J. M. Barlow, R. W. Eck, W. F. Hecker, and H. S. Levinson. *NCHRP Report 659: Guide for the Geometric Design of Driveways.* Transportation Research Board of the National Academies, Washington, D.C., 2010.
3. Dixon, K. K., R. D. Layton, M. Butorac, P. Ryus, J. L. Gattis, L. Brown, and D. Huntington. *Access Management Application Guidelines.* Transportation Research Board, Washington, D.C., 2016.
4. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
5. Stokes, A., W. A. Sarasua, N. Huynh, K. Brown, J. H. Ogle, A. Mammadrahimli, W. J. Davis, and M. Chowdhury. Safety Analysis of Driveway Characteristics along Major Urban Arterial Corridors in South Carolina. Presented at 95th Annual Meeting of the Transportation Research Board, Washington, D.C., Jan. 2016.
6. Hagenaur, G. F., J. Upchurch, D. Warren, and M. J. Rosenbaum. *Synthesis of Safety Research Related to Traffic Control and Roadway Elements.* Volume 1, Intersections. Report No. FHWA-TS-82-232, Federal Highway Administration, Washington, D.C., 1982.

CHAPTER 18

Driveway Vertical Geometry

Source: Photograph provided by the authors.

Description

Vertical geometry elements of a driveway include the change in grade from the roadway cross slope to the slope of the driveway apron (grade breaks), the minimum and maximum grade of the driveway, vertical curve design criteria, and vertical clearance to overhead obstacles (e.g., utility lines) (*1*, *2*).

Tables 58 through 60 follow.

Quantitative Analysis Methods

Motor Vehicle Operations

NCHRP Web-Only Document 151: Geometric Design of Driveways (*3*) documents a study comparing speeds of vehicles entering driveways with differing grades. The driveways studied had reasonably similar characteristics (e.g., throat width, curb radius, roadway speed, or right-hand travel lane width) other than the vertical grade. The driveways were divided into three groups by grade: flatter (1.5% to 5.0% grades), moderate (6.0% to 9.0% grades), and steeper (12.5% to 15.5% grades). Vehicle speeds observed prior to entering the driveway were similar for all three groups for right turns, but vehicle speeds were slightly lower at the driveway threshold and beyond the threshold for both right and left turns, as shown in Table 60.

Table 58. Multimodal operations and safety performance summary.

Access Management Technique	Performance Trends and Documented Performance Relationships: Operations					Safety				
										
Improve driveway vertical geometry.	↑ ●	↑ ◐	○	○	○	↑ ◐	○	↑ ◐	○	○

Table 59. General trends associated with improving driveway vertical geometry.

Mode	Operations	Safety
	Motor vehicles enter the driveway slightly faster (i.e., at a normal entering speed) (*3*).	Reduces vehicle and roadway damage from scraping caused by too-severe changes in grade rate (*2*). Allows vehicles to enter and exit the roadway at the design speed produced by the horizontal geometry, thereby reducing the speed differential of vehicles on the roadway (*4, 5*). Improves sight distance between the egressing vehicle and the approaching vehicle.
	Where the sidewalk is adjacent to the curb, helps achieve conformance with Americans with Disabilities Act requirements for the maximum cross-slope of the pedestrian access route (*5*).	Vehicle speeds increase slightly, but potential vehicle–pedestrian conflicts still take place at low speeds (*3*). Improves sight distance between the egressing vehicle and the approaching pedestrian.
	No documented effect.	Removes the potential for abrupt changes in pavement cross slope or elevation (e.g., bumps) that could cause a bicyclist to lose balance or control (*3*). Vehicle speeds increase slightly, but potential vehicle–bicycle conflicts still take place at low speeds. Improves sight distance between the egressing vehicle and the approaching cyclist.
	No documented effect beyond that generally observed for motor vehicle traffic.	No documented effect beyond that generally observed for motor vehicle traffic. Improves sight distance between the egressing vehicle and the approaching bus.
	No documented effect beyond that generally observed for motor vehicle traffic.	No documented effect beyond that generally observed for motor vehicle traffic. Improves sight distance between the egressing vehicle and the approaching truck.

Table 60. Comparisons of speeds of vehicles entering driveways with differing grades.

Driveway Grade	Average Speed (mph) by Location and Type of Turn: Prior to Driveway		Entering Driveway		15 Feet into Driveway	
	Right Turn	Left Turn	Right Turn	Left Turn	Right Turn	Left Turn
Flatter	14.1	10.3	5.5	10.5	7.2	10.0
Moderate	14.7	10.0	5.8	10.2	7.2	9.5
Steeper	14.5	9.6	5.1	8.7	5.9	8.1

Note: Prior to driveway = 25 feet prior for right turns and 1 lane width prior for left turns; entering driveway = 2 feet beyond driveway threshold. Grade categories: flatter = 1.5%–5.0%, moderate = 6.0%–9.0%, and steeper = 12.5%–15.5%.
Source: NCHRP Web-Only Document 151 (*3*).

Motor Vehicle Safety

NCHRP Report 659 (*5*) recommends a maximum grade break without a vertical curve of 10% for crests and 9% for sags and as low as 7% for driveways where vehicles towing trailers would be common, based on measurements of 31 driveways with scrape marks.

When a driveway slopes downward from the roadway edge [e.g., a downward-sloping driveway on the outside (or "high" side) of a superelevated roadway], sight distance for the motorist exiting the driveway may be restricted because the driveway is pointing upward and the vehicle's structure restricts the motorist's view of traffic (i.e., pedestrian, bicycle, transit, and truck) on the roadway (*6*). Reducing the driveway slope or providing a flatter landing area may improve sight distance.

Additional Information

- Chapters 17 and 19 in this guide.
- *Access Management Manual,* Second ed.: Section 13.7.7.
- *Access Management Application Guidelines*: Chapter 10, Driveway Design and Geometrics.
- *NCHRP Report 659: Guide for the Geometric Design of Driveways.*

References

1. Dixon, K. K., R. D. Layton, M. Butorac, P. Ryus, J. L. Gattis, L. Brown, and D. Huntington. *Access Management Application Guidelines.* Transportation Research Board, Washington, D.C., 2016.
2. Williams, K. M., V. G. Stover, K. K. Dixon, and P. Demosthenes. *Access Management Manual,* Second ed. Transportation Research Board of the National Academies, Washington, D.C., 2014.
3. Gattis, J. L., J. S. Gluck, J. M. Barlow, R. W. Eck, W. F. Hecker, and H. S. Levinson. *NCHRP Web-Only Document 151: Geometric Design of Driveways.* Transportation Research Board of the National Academies, Washington, D.C., July 2009.
4. Layton, R., G. Hodgson, and K. Hunter-Zaworski. Pedestrian and Bicyclist Impacts of Access Management. *Proceedings of the Third National Access Management Conference,* Fort Lauderdale, Fla., 1998.
5. Gattis, J. L., J. S. Gluck, J. M. Barlow, R. W. Eck, W. F. Hecker, and H. S. Levinson. *NCHRP Report 659: Guide for the Geometric Design of Driveways.* Transportation Research Board of the National Academies, Washington, D.C., 2010.
6. Florida Department of Transportation. *Driveway Information Guide*. Florida Department of Transportation, Tallahassee, Sept. 26, 2008.

CHAPTER 19

Driveway Throat Length

Source: Photograph provided by the authors.

Description

Driveway throat length is the distance from the outer edge of the traveled way of the roadway to the first point along the driveway at which there are conflicting vehicular traffic movements (*1*). This is the storage length available that is free of conflicts for vehicles entering or leaving a driveway.

Tables 61 and 62 follow.

Quantitative Analysis Methods

NCHRP Report 659: Guide for the Geometric Design of Driveways (*1*) provides detailed guidance on designing throat lengths to provide safe and efficient driveway operations. The HCM6 (*2*) can be used to estimate 95th percentile queue lengths on the driveway.

Table 61. Multimodal operations and safety performance summary.

	Performance Trends and Documented Performance Relationships									
	Operations					Safety				
Access Management Technique	Auto	Pedestrian	Bicycle	Transit	Truck	Auto	Pedestrian	Bicycle	Transit	Truck
Increase driveway throat length.	↑ ●	○	○	○	○	↑ ◐	↑ ◐	↑ ◐	○	○

Table 62. General trends associated with increasing driveway throat length.

Mode	Operations	Safety
	Provides sufficient space to allow vehicles to enter the site and circulate and, where parking can be directly accessed from the driveway, to wait for vehicles to back out of parking spaces without causing a queue of entering vehicles to back into the pedestrian crossing or roadway (*1*). Provides sufficient space to store vehicles exiting the site without blocking internal site circulation (*1*). On multi-lane entrances and exits, provides sufficient space for weaving maneuvers to position for a downstream turn (*1*).	Decreases the chances of a queue of entering vehicles developing that could back into the roadway (*1*). Gives entering drivers sufficient time to re-orient themselves before encountering conflicting internal site traffic or decision points related to turning or parking (*1*). On one-way driveways, provides sufficient length to place "Do not Enter" and "Wrong Way" signs that drivers can observe and react to in time (*1*).
	No documented effect.	Decreases the chances of a queue of entering vehicles developing that could back into the pedestrian crossing (*1*).
	No documented effect.	Decreases the chances of a queue of entering vehicles developing that could back into the bicycle facility or roadway (*1*).
	Similar to motor vehicles and trucks, where buses enter a site (e.g., a major shopping center or a transit center) instead of remaining on the roadway.	No documented effect beyond that generally observed for motor vehicle traffic.
	Provides sufficient space to store exiting trucks, buses, and vehicles with trailers without blocking internal site circulation (*1*).	No documented effect beyond that generally observed for motor vehicle traffic.

Additional Information

- Chapters 11, 16, and 17 in this guide.
- *Access Management Manual*, Second ed.: Section 13.7.5.
- *Access Management Application Guidelines*: Chapter 11, Design Guidelines for Driveway Throat Length.
- *NCHRP Report 659: Guide for the Geometric Design of Driveways.*

References

1. Gattis, J. L., J. S. Gluck, J. M. Barlow, R. W. Eck, W. F. Hecker, and H. S. Levinson. *NCHRP Report 659: Guide for the Geometric Design of Driveways.* Transportation Research Board of the National Academies, Washington, D.C., 2010.
2. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.

APPENDIX

Applications Guidance for Selected Quantitative Analysis Methods

Introduction

This appendix provides guidance on applying the quantitative analysis methods that appear most often in the guide. These methods can estimate performance measures that describe how access management techniques interact with the operations or safety performance of particular travel modes.

The interactions of access management techniques with travel modes can be described in two ways. One way is by presenting *absolute values* of a performance measure (e.g., average motor vehicle speeds would increase from 26.7 to 28.2 mph following installation of a non-traversable median). Another way is by presenting the *relative change* in a performance measure (e.g., average motor vehicle speeds would increase by 1.5 mph following installation of a non-traversable median). Calculating relative changes is often easier than calculating absolute values. This appendix focuses on demonstrating calculations that can be performed with nothing more than a scientific calculator. However, the appendix also provides guidance on where to turn for more information for performing complex calculations that require developing spreadsheets or applying specialized software.

Methods Described in this Appendix

The methods described in this appendix consist of the following from the *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. (HCM6):

- *HCM6 intersection delay methods.* These methods estimate the average motor vehicle control delay for a turning movement, approach, and/or intersection as a whole for signalized intersections, unsignalized intersections (i.e., minor street stop controlled), roundabouts, interchange ramp terminals, and alternative intersection and interchange forms. They can be used to evaluate the effects of access management techniques that alter turning movement patterns, traffic volumes, or both.
- *HCM6 arterial speed estimation methods.* These methods estimate the free-flow and average midblock running speeds of motor vehicle traffic along roadway links between signalized intersections or roundabouts. They also estimate the average travel speed of motor vehicles along longer sections of roadway, including the delays that occur at intersections. These methods can be used to evaluate the effects of access management techniques that alter the roadway geometry, number of access points, and/or on-street parking provisions.
- *HCM6 queue estimation methods.* These methods provide the 95th percentile back of queue and, sometimes, other percentile queues. They can be used to determine the size of an intersection's influence area and to size turn lane lengths and driveway throat lengths.

- *HCM6 multimodal level of service (MMLOS) methods.* These methods calculate pedestrian, bicycle, and transit level of service scores that estimate traveler satisfaction with quality of travel by these modes along a roadway section. In many cases, the effect of an access management technique on other modes is indirect, resulting from changes in average midblock motor vehicle speeds caused by the technique. However, in some cases, a particular access management technique may directly affect a non-auto mode's level of service score (e.g., the reduction or elimination of on-street parking).
- *HCM6 pedestrian and bicycle delay methods.* These methods calculate average pedestrian and bicycle delay at signalized intersections and roundabouts, along with average pedestrian delay crossing roadways at unsignalized locations. The methods can be used to evaluate the effects of access management techniques that change traffic volumes, change street widths, add pedestrian refuges, or are a combination of these.
- *Truck level of service.* This method evaluates the effect of changes in average truck speeds on overall truck level of service.
- *Crash modification factors.* These factors estimate the change in crash rate that would occur as a result of implementing a particular access management technique. CMFs are straightforward to apply; this appendix provides guidance on selecting appropriate CMFs that may be developed following the publication of this guide.
- *Vehicle crash models.* These models estimate the crash rate or total number of crashes that would occur given a particular set of conditions. They are applicable to a small number of access management techniques that affect factors included in one of these models.

Individual guide sections may present more quantitative techniques than are discussed in the appendix. Those techniques that are not discussed are considered straightforward to apply and do not require additional explanation. In addition, other analysis tools (e.g., simulation) exist that can also be used to estimate motor vehicle operations and that may be equally or more appropriate to use in a given circumstance. However, describing how to use these alternative tools is beyond the scope of this guide. HCM6 techniques are described because they are well researched, well documented, and widely used.

Table A1 lists the analysis methods described in this appendix. For each group of access management techniques described in this guide, the table indicates whether an analysis method (a) can be used to calculate relative changes in operations or safety without calculating absolute values first, (b) can only calculate relative changes when an absolute value is calculated first, or (c) is not applicable to any technique in the group. A given method will typically be applicable to only one or a few of the access management techniques included in a given group.

HCM6 Intersection Delay Methods

Chapters 19 through 23 in the HCM6 (*1*) provide methods for assessing motor vehicle operations at signalized intersections (Chapter 19), two-way stop-controlled intersections (Chapter 20), all-way, stop-controlled intersections (Chapter 21), roundabouts (Chapter 22), and interchange ramp terminals and alternative intersections (Chapter 23). The effect of access management techniques that alter turning-movement patterns, traffic volumes, or both at individual access points or intersections can be evaluated using these chapters' methods by calculating the resulting change in average control delay and/or motor vehicle level of service. Once average delay to the major street through movement is determined at each intersection of interest, an average travel speed along the major street can also be determined, as described in the next section.

With the exception of the delay method for roundabouts, which can be performed by hand or automated in a simple spreadsheet, the intersection delay methods described in the HCM6 are only

Table A1. Quantitative method applicability by access management technique group.

Access Management Technique Group	HCM6 Vehicle Delay	HCM6 Arterial Speed	HCM6 Queues	HCM6 MMLOS	HCM6 Pedestrian and Bike Delay	Truck LOS	CMFs	Bowman Crash Rate Models	Potts Pedestrian Crash Model	Carter Intersection Safety
Restrict left-turn movements	◐	◐	○	◐	◐	◐	●	○	○	○
Non-traversable medians	○	●	○	●	◐	●	●	◐	○	○
Two-way left-turn lanes	○	●	○	●	○	●	●	◐	○	○
Frontage and service roads	◐	◐	◐	◐	◐	◐	●	○	○	○
Unsignalized median openings	◐	○	○	○	◐	○	●	◐	○	○
Traffic signal spacing	◐	◐	○	◐	◐	◐	○	○	○	○
Number and spacing of access points	○	●	○	●	○	●	●	◐	○	○
Interchange areas	◐	○	◐	○	○	○	○	○	○	○
Left-turn lanes	◐	◐	◐	●	○	●	●	○	○	○
Right-turn lanes	◐	◐	◐	●	○	●	●	○	◐	◐
Driveway channelization	○	○	○	○	○	○	○	○	○	○
Alternative intersections and interchanges	◐	○	○	○	○	○	●	○	○	○
Parking and stopping restrictions	○	●	○	●	○	●	●	○	○	◐
Roundabouts	◐	○	◐	○	◐	○	○	○	○	○
Driveway sight distance	○	○	○	●	○	○	○	○	○	○
One-way driveways	◐	●	○	●	○	○	○	○	○	○
Driveway width	○	○	○	○	○	○	○	○	○	○
Driveway vertical geometry	○	○	○	○	○	○	○	○	○	○
Driveway throat length	○	○	◐	○	○	○	○	○	○	○

Note: ● = Relative change can be estimated without calculating absolute values. Absolute values can also be calculated.
◐ = Relative change can be estimated by calculating absolute values first.
○ = Method not applicable to this group of access management techniques.

practical to apply by using specialized software, given the number of computations involved. A number of commercial software packages are available that perform these calculations for some or all of these intersection types. In addition, STREETVAL, a research-grade computational engine that can estimate delay at signalized intersections, is available on the HCM6 Volume 4 website (www.HCM6volume4.org, free to access but requires a one-time registration).

The input data required to apply these methods are listed in Exhibits 19-11 and 19-12 in the HCM6 (signalized intersections), Exhibit 20-15 (two-way stop-controlled intersections), Exhibit 21-9 (all-way stop-controlled intersections), Exhibit 22-9 (roundabouts), and Exhibit 23-21 (signalized ramp terminals). In addition, the "Required Data and Sources" section starting on Page 23-71 describes input data requirements for certain alternative intersection forms that go beyond the data required for signalized intersections or two-way stop-controlled intersections. At a minimum, the HCM6 delay methods require the analyst to supply traffic volumes and lane configurations by movement, plus left-turn phasing for signalized intersections and special geometric conditions (e.g., presence of two-way left-turn lanes or median storage) for two-way stop-controlled intersections. Other input data can be defaulted, but the fewer default values that are used the greater is the chance that the end result is likely to be accurate. In particular, the heavy vehicle percentage, peak hour factor, and (for traffic signals) saturation flow rate, cycle length, and minimum green time by phase are the default values with the greatest potential impact on the end result. In areas with high levels of pedestrian activity, pedestrian volumes are also important to account for.

NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the Highway Capacity Manual (*2*) provides simplified versions of the HCM6 signalized intersection and roundabout delay methods that can be applied by hand or by using one of the computational engines (spreadsheets) available in the Application Guides section of the HCM6 Volume 4 website. A simplified delay method and spreadsheet are also provided for two-way stop-controlled intersections; however, this method may not be appropriate for analyzing some access management techniques because it assumes the presence of left-turn lanes on the major street, no median, no U-turns, and no ability to make two-stage left turns, among other things.

HCM6 Arterial Travel Speed Methods

Techniques Affecting Free-Flow Speed

Some access management techniques affect a roadway's free-flow speed, "the average running speed of through vehicles traveling along a segment under low-volume conditions and not delayed by traffic control devices or other vehicles. It reflects the effect of the street environment on driver speed choice" (*1*). Changes in the free-flow speed affect the average midblock motorized vehicle speed, although not on a one-to-one basis. As demonstrated in the next section, a 1 mph increase in free-flow speed typically results in a 0.85–0.95 mph increase in average midblock speed at volumes of 500 vehicles per lane or lower. But a 1 mph increase in free-flow speed but can be potentially as low as 0.65 mph in situations with a combination of high free-flow speeds, high traffic volumes, short traffic signal spacing, and many access points.

Estimating Changes in Free-Flow Speed

The following types of access management techniques affect a roadway's free-flow speed: (a) installing a non-traversable (restrictive) median, (b) reducing the number of access points, and (c) removing on-street parking. The effects of these techniques on free-flow speed are as follows:

- **Non-traversable median.** Exhibit 18-11 in the HCM6 gives the change in roadway free-flow speed resulting from a conversion from an undivided roadway or a non-restrictive median to a restrictive (i.e., non-traversable median) (*1*). The change in free-flow speed (in mph) equals $1.5\ p_{rm} - 3.7\ p_{rm}, p_{\text{curb}}$, where p_{rm} is the proportion of the link length (decimal) with a restrictive median and p_{curb} is the proportion of the link length (decimal) with a curb on the right side of the roadway. When a non-restrictive median is implemented, the free-flow speed increases where there is no curb on the right side of the roadway and decreases where there is a curb.
- **Access point density.** Equation 18-3 and Exhibit 18-11 in the HCM6 give the reduction in roadway free-flow speed due to access point density (*1*). This reduction (in mph) equals $-0.078\ D_a/N_{\text{th}}$, where D_a is the number of access points per mile (considering both sides of the roadway but only those accessible to or from the direction of travel), and N_{th} is the number of through lanes in the direction of travel. Thus, reducing the number of access points increases the free-flow speed.
- **Parking restrictions.** Exhibit 18-11 in the HCM6 indicates that roadway free-flow speed increases by 0.03 mph for each 1% reduction in the percentage of street length where on-street parking is allowed (*1*). Thus, eliminating on-street parking increases the free-flow speed by

up to 3 mph. In most cases, the speed increase will be lower, as right-turn lanes, driveways, and unsignalized intersections between traffic signals will reduce the street length where parking is allowed. In addition, parking would often have already been restricted in driveways.

Estimating Changes in Average Midblock Running Speed from Changes in Free-Flow Speed

The average midblock running speed is an input to the pedestrian and bicycle LOS methods in the HCM6, described later in this appendix. The average midblock running speed is also used in combination with delay at intersections to determine average motor vehicle travel speeds along a roadway segment or facility. When the free-flow speed changes, so does the average midblock running speed, although by a smaller amount. This section presents two methods for relating the average midblock running speed of motor vehicles to the free-flow speed. The first method is a graphical generalized approach that provides pre-calculated values for a variety of situations. The second method is a direct calculation using the HCM6's equations. Either method can determine either (1) an absolute value for the average midblock running speed for a given set of conditions or (2) the change in average midblock running speed given a change in free-flow speed.

Generalized Approach

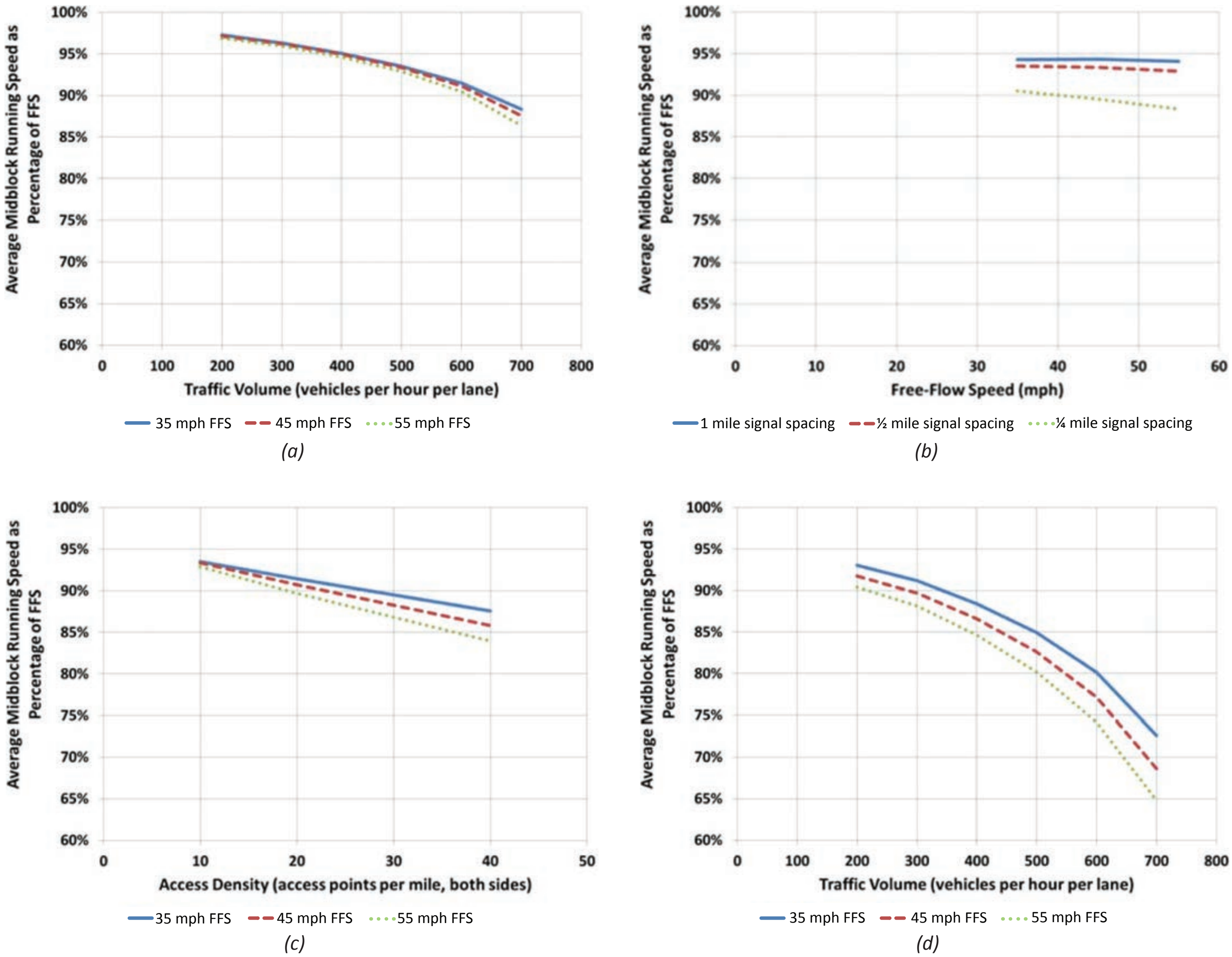
Figure A1 shows average midblock running speed as a percentage of free-flow speed for various combinations of free-flow speeds, per-lane traffic volumes, traffic signal spacing, and access spacing. To use the figure, find the graph with the conditions most closely matching the situation being analyzed. The assumptions used to develop these graphs are presented at the bottom of the figure. In many cases, the average midblock running speed is approximately 85%–95% of the free-flow speed, but in more extreme situations (i.e., high volumes, high free-flow speed, short signal spacing, and many access points) it can be as low as 65% of the free-flow speed. In the absence of other information about the free-flow speed, it can be assumed that the free-flow speed is 5 mph greater than the posted speed limit.

Example 1. As an example of how to use these graphs to calculate an absolute speed value, assume a roadway has a 35-mph free-flow speed, 500 vehicles per hour per lane, ½-mile signal spacing, and 30 access points per mile (including public street intersections). Figure A1*c* shows that the average midblock running speed would be approximately 90% of the free-flow speed, or about 31.5 mph. Further adjustments to free-flow speed related to median presence and on-street parking can be made by using the relationships given above.

Example 2. As an example of how to use these graphs to calculate a relative change in speed, assume the same roadway. Curbside parking is allowed along this roadway, except within 30 feet of an access point. The average access width is 30 feet (i.e., the length of no-parking zone associated with each access is 90 feet). Given 15 access points on each side of the street, a total of 1,350 feet out of the 2,640 feet between traffic signals is already designated for no parking. If parking is prohibited along the remaining 1,290 feet (i.e., 49% of the section length), the free-flow speed would be expected to increase by 1.5 mph (49×0.03). From Figure A1*c*, the average midblock running speed would be expected to increase by 90% of this value, or about 1.35 mph.

Direct Calculation Approach

Equations from the HCM6 can directly estimate the average midblock running speed for a given set of conditions. To determine the relative change in running speed, calculate the speed twice, once for the *before* condition and once for the *after* condition.



Note: Assumptions used in each graph are as follows:

(a) Number of lanes = 2 per direction, ½-mile signal spacing, 10 access points per mile.
(b) Number of lanes = 2 per direction, 10 access points per mile, 500 vehicles per hour per lane.
(c) Number of lanes = 2 per direction, ½-mile signal spacing, 500 vehicles per hour per lane.
(d) Number of lanes = 2 per direction, ¼-mile signal spacing, 40 access points per mile.

Figure A1. Average midblock running speed as a percentage of free-flow speed or FFS: (a) volume and free-flow speed, (b) free-flow speed and signal spacing, (c) access density and free-flow speed, and (d) volume and free-flow speed, many access points and signals.

Step 1. Determine the base free-flow speed. The base free-flow speed is a function of the posted speed, median and curb presence, on-street parking provision, and access point density. The base free-flow speed is calculated by using Equation A1, which is derived from Equation 18-3 in the HCM6.

$$S_{fo} = S_0 + f_{cs} + f_A + f_{pk} \qquad \text{(A1)}$$

where

S_{fo} = base free-flow speed (mph)
S_0 = speed constant, from Table A2 (mph)

Table A2. Base free-flow speed adjustment factors.

Speed Limit (mph)	Speed Constant S_0 (mph)[a]	Median Type	Percent with Restrictive Median (%)	Adjustment for Cross Section f_{CS} (mph)[b]	
				No Curb	Curb
25	37.4	Restrictive	20	0.3	−0.9
30	39.7		40	0.6	−1.4
35	42.1		60	0.9	−1.8
40	44.4		80	1.2	−2.2
45	46.8		100	1.5	−2.7
50	49.1	Nonrestrictive	na	0.0	−0.5
55	51.5	No median	na	0.0	−0.5

Access Density (points/mi)	Adjustment for Access Points f_A by Lanes N_{th} (mph)[c]			Percent with On-Street Parking (%)	Adjustment for Parking f_{pk} (mph)[d]
	1 Lane	2 Lanes	3 Lanes		
0	0.0	0.0	0.0	0	0.0
2	−0.2	−0.1	−0.1	20	−0.6
4	−0.3	−0.2	−0.1	40	−1.2
10	−0.8	−0.4	−0.3	50	−1.5
20	−1.6	−0.8	−0.5	60	−1.8
40	−3.1	−1.6	−1.0	80	−2.4
60	−4.7	−2.3	−1.6	100	−3.0

Note: na = not applicable.
[a] $S_0 = 25.6 + 0.47 S_{pl}$, where S_{pl} = posted speed limit (mph).
[b] $f_{CS} = 1.5\,p_{rm} - 0.47\,p_{curb} - 3.7\,p_{curb}, p_{rm}$, where p_{rm} = proportion of link length with restrictive median (decimal) and p_{curb} = proportion of segment with curb on the right side (decimal).
[c] $f_A = -0.078\,D_a / N_{th}$, where D_a = access point density on segment, considering both sides of the roadway but only counting those accessible to or from the direction of travel (points/mi), and N_{th} = number of through lanes in the direction of travel;
[d] $f_{pk} = -3.0 \times$ proportion of link length with on-street parking available on the right side (decimal).
Source: Adapted from *Highway Capacity Manual,* 6th ed., Exhibit 18-11 (*1*).

f_{cs} = adjustment for cross-section (mph), from Table A2
f_A = adjustment for access point density (mph), from Table A2
f_{pk} = adjustment for on-street parking (mph), from Table A2

All of the values needed for Equation A1 may be obtained directly from Table A2 or from the equations provided in the notes below Table A1.

Step 2. Adjust the free-flow speed for short traffic signal spacing. Shorter distances between traffic signals have been found to result in lower free-flow speeds, all other factors being equal (*1*, *3*). Equations A2 and A3, derived from Equations 18-4 and 18-5 in the HCM6 (*1*), adjust the base free-flow speed to account for this effect.

$$f_L = 1.02 - 4.7\frac{S_{fo} - 19.5}{\max(L, 400)} \le 1.0 \qquad \text{(A2)}$$

$$S_f = S_{fo} f_L \ge S_{pl} \qquad \text{(A3)}$$

where

f_L = adjustment for traffic signal spacing (unitless)
S_f = free-flow speed (mph)
L = segment length (ft), which is the distance between adjacent signalized intersections
S_{pl} = posted speed limit (mph)

Step 3. Calculate the average midblock running speed. The following equations, derived from Equations 18-6, 18-7, and 18-15, respectively, in the HCM6 (*1*), can estimate the average midblock running speed for a given free-flow speed, traffic volume, and access point density, for streets with signalized intersections (i.e., no roundabouts or intersections where the major street is stop controlled).

$$f_v = \frac{2}{1+\left(1-\dfrac{v_m}{52.8N_{\text{th}}S_f}\right)^{0.21}} \tag{A4}$$

$$t_R = \frac{4.0}{0.0025L} + \frac{3,600L}{5,280S_f}f_v + \frac{n_{ap}L}{5,280}d_{ap} \tag{A5}$$

$$S_R = \frac{3,600L}{5,280t_R} \tag{A6}$$

where

f_v = proximity adjustment factor
t_R = average segment running time (s)
n_{ap} = access point density, considering both sides of the roadway, but only counting those accessible to or from the direction of travel (points/mi)
d_{ap} = average through vehicle delay per access point, from Table A3 (s/access point)
v = average midblock volume (veh/h)
v_m = average midblock 15-minute demand flow rate (veh/h) = v/PHF, where PHF = peak hour factor = $v/(4 \times$ peak 15-min volume)
N_{th} = number of through lanes
S_R = average midblock running speed (mi/h)

Example 3. Assume a roadway with the following characteristics. They are 30-mph posted speed, 5 lanes (two travel lanes in each direction and a two-way left-turn lane), ½-mile signal spacing, 30 access points per mile, on-street parking for 50% of the segment length, curb present,

Table A3. Average delay due to turning vehicles at access points.

Midsegment Volume (vehicles per hour per lane)	Through Vehicle Delay (s/access point) by Number of Through Lanes		
	1 Lane	2 Lanes	3 Lanes
200	0.04	0.04	0.05
300	0.08	0.08	0.09
400	0.12	0.15	0.15
500	0.18	0.25	0.15
600	0.27	0.41	0.15
700	0.39	0.72	0.15

Note: Based on 10% right turns and 10% left turns on average from the roadway at a typical access point. Adjust proportionally for other turn percentages. Assumes no exclusive turn lanes are provided at a typical access point. Reduce adjusted values by 50% for each movement provided with an exclusive turn lane of adequate length or prohibited (e.g., 50% for a left-turn lane provided but no right-turn lane, 100% for left- and right-turn lanes provided, and 100% for left turns prohibited and a right-turn lane provided).
Source: Highway Capacity Manual, 6th ed., Exhibit 18-13 (*1*).

no right-turn lanes at access points, 1,000 vehicles per hour in the direction of travel, and a peak hour factor of 0.92. The average midblock running speed is calculated as follows:

Step 1. The following values are obtained from Table A2:

- Speed constant $S_0 = 39.7$ mph
- Cross-section adjustment $f_{cs} = -0.5$ mph (nonrestrictive median + curb)
- Access-point density adjustment $f_A = -1.2$ mph (2 lanes, interpolate for 30 points/mi)
- On-street parking adjustment $f_{pk} = -1.5$ mph (interpolate for 50% parking)

From Equation A1, the base free-flow speed is then 36.5 mph.

Step 2. The traffic signal spacing adjustment f_L is determined from Equation A2, using a segment length of 2,640 ft (½ mi), and found to be 0.99. The free-flow speed is then determined to be 36.1 mph, using Equation A3.

Step 3. Equation A4 is used to determine the proximity adjustment, using inputs of 1,087 veh/h (= 1,000 veh/h/0.92), 2 through lanes, and a free-flow speed of 36.1; the factor f_v is determined to be 1.035.

Equation A5 is then used to determine the average segment running time t_R. From Table A3, the average delay per vehicle per access point d_{ap} is initially determined by interpolation to be 0.32 s/point, using inputs of 2 through lanes and a 15-min demand flow rate of 544 veh/h/ln (= 1,087/2). Because there is a two-way left-turn lane but there are no right-turn lanes, this initial value is reduced by 50% to a final value of 0.16 s/access point. All other inputs to the equation have been given or previously calculated, and t_R is determined to be 54.6 s.

Finally, Equation A6 is used to calculate the average midblock running speed S_R, which is determined to be 33.0 mph, which is 91% of the free-flow speed.

Example 4. Assume the same roadway, but with on-street parking prohibited. In **Step 1**, the base free-flow speed increases by 1.5 mph to 38.0 mph. In **Step 2**, the free-flow speed becomes 37.6 mph. In **Step 3**, the proximity adjustment becomes 1.034, the average segment running time becomes 52.5 s, and the average midblock running speed becomes 34.3 mph. Compared with the situation in Example 3, the average running speed has increased by 1.3 mph (i.e., it increased by 87% of the increase in the base free-flow speed).

Estimating Average Travel Speed

Average travel speed is based on the combination of the running time for a segment with the average delay for the through movement at the downstream, signalized intersection (or another boundary intersection, such as a roundabout). Average travel speed can be calculated with Equation A7, which is based on Equation 18-15 in the HCM6 (*1*):

$$S_T = \frac{3{,}600L}{5{,}280(t_R + d_t)} \qquad \text{(A7)}$$

where S_T is the average travel speed (mi/h) and d_t is the average delay to the through movement at the downstream boundary intersection.

Queue Estimation Methods in the HCM6

Chapter 19 in the HCM6 (*1*) provides a method for assessing average and any percentile back-of-queue length at signalized intersections. The HCM6 also provides methods for estimating 95th percentile queue lengths at two-way stop-controlled intersections (Chapter 20), all-way stop-controlled intersections (Chapter 21), and roundabouts (Chapter 22). The effect of access management techniques that alter turning movement patterns, traffic volumes, or both at individual access points or intersections can be evaluated by using the methods in these chapters, by calculating the resulting 95th percentile queue length and comparing the result with the available queue storage length.

With the exception of the method for roundabouts, which can be performed by hand or by automation in a simple spreadsheet, the queue estimation methods described in the HCM6 are only practical to apply with specialized software, given the number of computations involved. However, calculating a 95th percentile queue can be done by hand using just one equation, once the capacity of a lane group or approach has been determined in the process of calculating intersection delay. A number of commercial software packages are available that can perform these calculations. The required input data are the same as described earlier for the HCM6 intersection delay methods.

NCHRP Report 825 (*2*) provides simplified versions of the HCM6's methods for 95th percentile queue estimation, which can be done by hand or in a spreadsheet. At the time of this writing, the signalized intersection computational engine available in the Application Guides section of the HCM Volume 4 website (hcmvolume4.org) could calculate queues, but the engines for other intersection forms could not calculate queues. This guide's simplified method for two-way stop-controlled intersections, however, may not be appropriate for analyzing some access management techniques, because it assumes the presence of left-turn lanes on the major street, no median, no U-turns, and no ability to make two-stage left turns, among other things.

Multimodal Level of Service Methods in the HCM6

Chapter 18 in the HCM6 (*1*) provides a unified set of methods for estimating pedestrian, bicycle, and on-street transit LOS. Key features of these methods are (a) the LOS determined for each travel mode, as well as each mode's underlying level of service score, can be directly compared with each other and (b) the LOS values were developed from actual traveler perceptions. These methods are particularly well suited for evaluating how changes in the allocation of roadway right-of-way among different modes affects each mode's quality of service, but they can also be used to evaluate the impact of various access management techniques.

In many cases, the impact of an access management technique on a mode's LOS is indirect: the technique changes the speed, volume, or both of motorized traffic on the roadway and thereby influences the mode's LOS. In other cases, the impact is direct: for example, changing the amount of occupied on-street parking directly influences both pedestrian and bicycle LOS, while changing the number of access points per mile directly influences bicycle LOS.

The HCM6 provides multimodal LOS methods for links (between signalized intersections), signalized intersections and segments (combining links and intersections), and facilities (multiple consecutive segments). A link-based evaluation requires the least amount of data and calculations and is sufficient for many applications, including evaluating the effects of many access management techniques. However, a segment-based evaluation (including evaluating modal LOS for intersections) may be appropriate for the following types of techniques: (a) techniques that result in substantial changes in turning-movement volumes that conflict with pedestrians and bicycles, (b) techniques that change the access density, and (c) techniques that change pedestrian delay crossing a street in the middle of the block. A segment-based evaluation is also necessary when desired to directly compare bicycle and pedestrian LOS scores with transit LOS scores, because transit LOS is only calculated at a segment level.

The following section focuses on link-based evaluations and discusses relevant aspects of segment-based evaluations. All calculations can be performed by hand or readily input into a spreadsheet. A computational engine (spreadsheet) for calculating multimodal LOS along a link is available in the Application Guides section of the HCM Volume 4 website (hcmvolume4.org).

Pedestrian LOS

Links

Pedestrian LOS (PLOS) for a roadway link is influenced by a number of factors. They include sidewalk width and separation from traffic, traffic volumes and speeds, and presence of buffers such as street trees. The HCM6 method calculates a PLOS score, which then translates into an LOS letter as shown in Table A4.

Equation A8, adapted from Equation 18-32 in the HCM6 (*1*), shows the component factors used to determine the PLOS score. A change in any one of these component factors changes the PLOS score on a one-to-one basis, making it easy to identify relative changes in PLOS due to particular access management techniques, without having to perform the full set of calculations.

$$PLOS_l = 6.0468 + F_w + F_v + F_S \quad \text{(A8)}$$

where

$PLOS_l$ = pedestrian LOS score for link
F_w = cross-section adjustment factor
F_v = motorized vehicle volume adjustment factor
F_S = motorized vehicle speed adjustment factor

The cross-section adjustment factor F_w is a function of the sidewalk width, the separation of the sidewalk from the street, the presence of physical buffers or barriers between the street and sidewalk, and the effective separation of moving traffic from the curb (including such factors as the width of any parking, shoulder, or bicycle lanes, and parking occupancy). Figure A2 shows the key dimensions used in determining PLOS. Note that the width of the gutter and curb (if present) is not included in any of the dimensions.

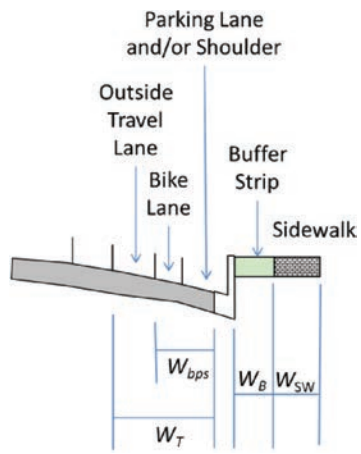
Equation A9, adapted from Equation 18-33 in the HCM6 (*1*), is used to determine the cross-section adjustment factor.

$$F_w = -1.2276 \ln(W_v + 0.5W_{bps} + 50 p_{pk} + W_B f_B + W_A f_{SW}) \quad \text{(A9)}$$

Table A4. Pedestrian LOS criteria.

LOS	Segment-Based PLOS Score	Link-Based PLOS Score
A	≤ 2.00	≤ 1.50
B	> 2.00–2.75	> 1.50–2.50
C	> 2.75–3.50	> 2.50–3.50
D	> 3.50–4.25	> 3.50–4.50
E	> 4.25–5.00	> 4.50–5.50
F	> 5.00	> 5.50

Note: The HCM6 also considers pedestrian density on the sidewalk when determining pedestrian LOS. However, pedestrian density only influences the result at very high pedestrian volumes (> 1,000 pedestrians per hour) and therefore is not included.
Source: Derived from the *Highway Capacity Manual,* 6th ed., Exhibit 18-2 (*1*).



Source: Adapted from *NCHRP Report 825*, Exhibit 99 (*2*).

Figure A2. Key dimensions used in determining pedestrian LOS.

where

ln = natural logarithm
W_T = total width of outside through lane, bicycle lane, parking lane, and shoulder (ft)
W_{SW} = available sidewalk width, not including landscape buffer or furnishing zone (ft)
v = average midblock volume in the direction of travel closest to the sidewalk (veh/h)
W_v = effective total width of outside through lane, bicycle lane, and shoulder as a function of traffic volume (ft) = W_T if $v_m > 160$ veh/h or $W_{SW} > 0$, then $W_v = W_T$; if not (i.e., otherwise), $W_v = W_T \times (2 - 0.005\ v_m)$
W_{bps} = total width of bicycle lane, parking lane, and shoulder (ft)
p_{pk} = proportion of on-street parking occupied (decimal)
W_B = width of landscape buffer or furnishing zone (ft)
f_B = buffer area coefficient = 5.37 for any continuous barrier at least 3 feet high located between the sidewalk and the outside edge of roadway; otherwise, use 1.0
W_A = adjusted sidewalk width = $\min(W_{SW}, 10)$ (ft)
f_{SW} = sidewalk coefficient = $6.0 - 0.3\ W_A$

Equations A-10 and A-11, adapted from Equations 18-34 and 18-35, respectively, in the HCM6 (*1*), are used to determine the motorized vehicle volume and speed adjustment factors.

$$F_v = 0.0091 \frac{v_{ma}}{4N_{th}} \quad \text{(A10)}$$

$$F_s = 4\left(\frac{S_R}{100}\right)^2 \quad \text{(A11)}$$

where

v_{ma} = adjusted average midblock 15-min demand flow rate (veh/h) = $\max(v_m, 4N_{th})$
N_{th} = number of through lanes in the direction of travel closest to the sidewalk
S_R = average motorized vehicle midblock running speed (mph)

Example 5. Assume that, as a result of an access management technique, average motorized vehicle midblock running speeds increase by 2 mph, from 42 to 44 mph. From Equation A11, the before-and-after values of F_s are 0.71 and 0.77, respectively. Because nothing else changes that would affect PLOS, the PLOS value would go up (i.e., get worse) by 0.06 point as a result of the technique. The LOS letter would likely stay the same, as 0.06 is much less than the width of the range used to determine LOS letters (i.e., 1.00 point for links and 0.75 point for segments).

Example 6. Assume the roadway used in Example 3, with the following additional assumptions. They are 80% of the available parking is occupied on average, the sidewalk width is 6 feet, there is no landscape buffer or bicycle lane, the parking lane width (not including the gutter) is 8 feet, and the outside travel lane width is 12 feet. PLOS is then calculated as follows:

- *Cross-section adjustment factor.* Because a sidewalk is provided, W_v equals W_T, the total width of the outside travel lane, bicycle lane, parking lane, and shoulder ($12 + 0 + 8 + 0 = 20$ feet). W_{bps} equals the sum of the bicycle lane, parking lane, and shoulder widths, or 8 feet. The proportion of occupied on-street parking p_{pk} is the proportion of the street where on-street parking is provided, multiplied by the percentage of the parking that is occupied: $0.5 \times 0.8 = 0.4$. The buffer width is 0 feet and because there are no street trees or other forms of barriers, the buffer area coefficient is 1.00. Because the sidewalk width is less than 10 feet, the adjusted sidewalk width W_A is the same as the sidewalk width (6 feet); the sidewalk coefficient then computes to be 4.2. Entering these values into Equation A9 gives a value of F_w of −5.201.
- *Motorized vehicle volume adjustment factor.* From Example 3, $v_m = 1{,}087$ veh/h and $N_{th} = 2$ lanes. Entering these values into Equation A10 gives a value of F_v of 1.236.
- *Motorized vehicle speed adjustment factor.* From Example 3, $S_R = 33.0$ mph. Applying Equation A11 gives a value of F_s of 0.436.
- *Pedestrian level of service score.* Entering the calculated adjustment factor values into Equation A8 gives a PLOS score of 2.52. From Table A4, this score for a link corresponds to LOS C, just beyond the threshold for LOS B.

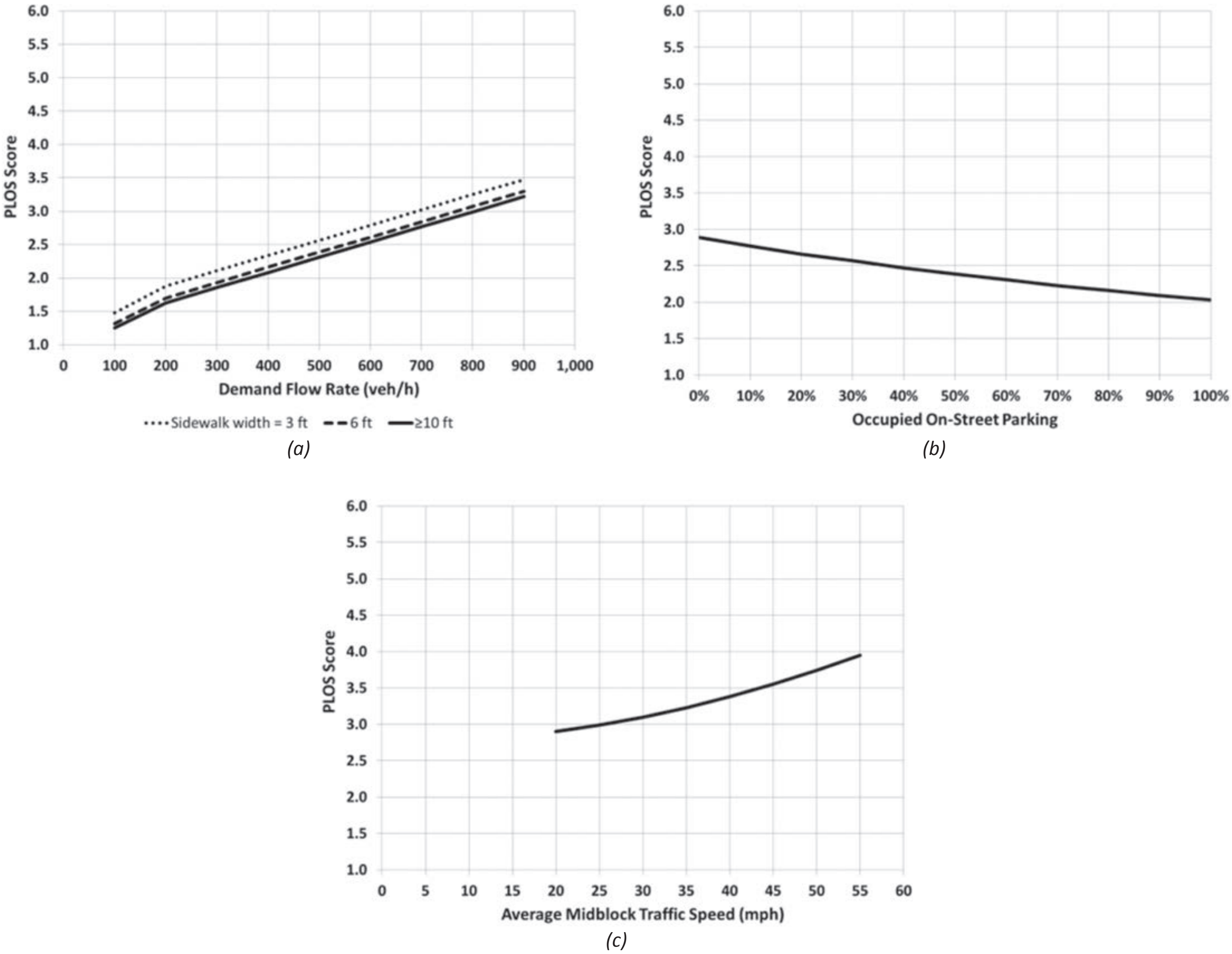
Figure A3 demonstrates the sensitivity of PLOS to various factors influenced by access management techniques.

Segments

Midblock pedestrian crossing delay is a factor in determining PLOS at the segment level. It is determined as the lesser of (a) average pedestrian delay making a midblock pedestrian crossing (if allowed) and (b) delay diverting to the nearest signalized intersection to cross. Providing a non-traversable median along a roadway makes it possible for pedestrians to cross the street in two stages, which reduces pedestrian delay, while widening the roadway (e.g., to add a turn lane) increases pedestrian delay.

Step 8 of the pedestrian LOS methodology in the HCM6 (starting on page 18-54) describes how to calculate a "roadway crossing difficulty factor" (*1*), while Step 9 applies this factor to the calculation of PLOS for a segment. Chapter 19 in the HCM6 estimates pedestrian delay and PLOS at the traffic signal, while the pedestrian delay methodology in Chapter 20 is used to estimate midblock crossing delay, including accounting for driver-yielding behavior (*1*). See the Pedestrian and Bicycle Delay section later in the appendix for more details.

Figure A4 shows the sensitivity of segment PLOS to street-crossing delay for various levels of link PLOS, under the assumption that intersection PLOS (used in calculating segment PLOS) is equal to link PLOS. The roadway crossing difficulty factor is constrained to minimum and maximum values beyond which it has no additional effect, as indicated by the horizontal lines in the figure. In addition, the street-crossing delay used in calculating the factor is capped at 60 seconds.



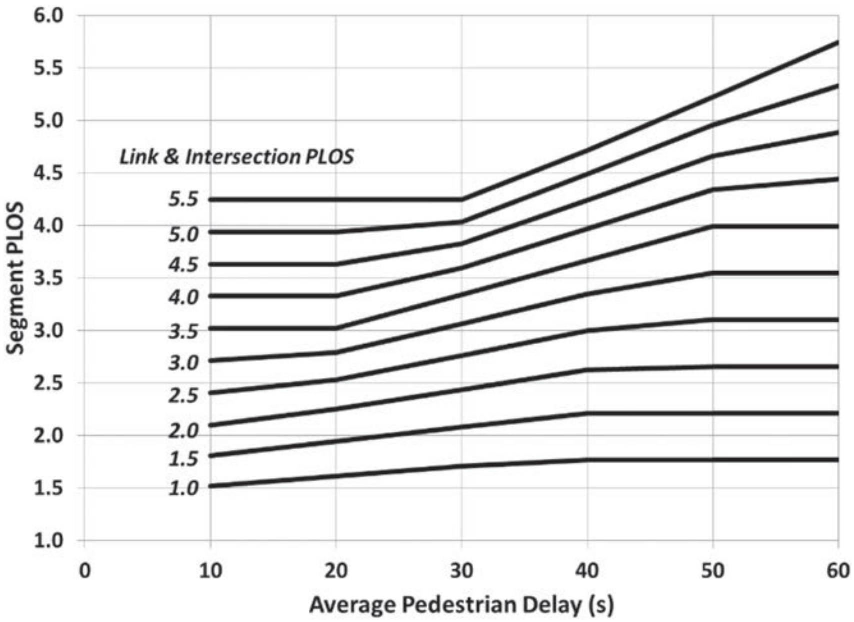
Note: Assumptions used in each graph are as follows:

(a) Outside lane demand flow rate = 500 veh/h; no landscape buffer or street trees, outside travel lane width = 12 feet; parking lane width = 8 feet; and traffic speed = 35 mph.

(b) Occupied on-street parking = 50%; no landscape buffer or street trees, outside travel lane width = 12 feet; parking lane width = 8 feet; and traffic speed = 35 mph.

(c) Outside lane demand flow rate = 500 veh/h; occupied on-street parking = 50%; no landscape buffer or street trees, outside travel lane width = 12 feet; and parking lane width = 8 feet.

Figure A3. Sensitivity of link PLOS to factors influenced by access management techniques: (a) volume and sidewalk width, (b) occupied on-street parking, and (c) average midblock traffic speed.



Note: Assumptions used to develop the graph include link PLOS = intersection PLOS, segment length = ½ mile, average pedestrian delay at the traffic signal at the end of the segment = 50 seconds, and average pedestrian walking speed = 4 feet per seconds.

Figure A4. Sensitivity of segment PLOS to street-crossing delay.

Bicycle LOS

Links

A number of factors influence bicycle LOS (BLOS) for a roadway link. They include bicycle lane presence, on-street parking presence, separation of bicycles from motorized traffic, traffic volumes and speeds, heavy vehicle percentage, and pavement condition. The HCM6 method calculates a BLOS score, which translates into a LOS letter as shown in Table A5.

Equation A12, adapted from Equation 18-41 in the HCM6 (*1*), shows the component factors used to determine the BLOS score. A change in any one of these component factors changes the BLOS score on a one-to-one basis, making it easy to identify relative changes in BLOS due to particular access management techniques, without having to perform the full set of calculations.

$$BLOS_l = 0.760 + F_w + F_v + F_s + F_p \qquad \text{(A12)}$$

where $BLOS_l$ is the bicycle LOS score for link and F_p is the pavement condition adjustment factor.

Table A5. Bicycle LOS criteria.

LOS	Segment-Based PLOS Score	Link-Based PLOS Score
A	≤ 2.00	≤ 1.50
B	> 2.00–2.75	> 1.50–2.50
C	> 2.75–3.50	> 2.50–3.50
D	> 3.50–4.25	> 3.50–4.50
E	> 4.25–5.00	> 4.50–5.50
F	> 5.00	> 5.50

Source: Derived from *Highway Capacity Manual*, 6th ed., Exhibit 18-3 (*1*).

The cross-section adjustment factor F_w is generally a function of the outside travel lane width, bicycle lane and shoulder width (if present), and parking presence and occupancy. Figure A5 shows the key dimensions used in determining BLOS. Note that the width of the parking lane or shoulder is included in these dimensions only when completely unoccupied and that the gutter and curb (if present) are never included.

Equation A13, adapted from Equation 18-42 in the HCM6 (*1*) determines the cross-section adjustment factor:

$$F_w = -0.005W_e^2 \tag{A13}$$

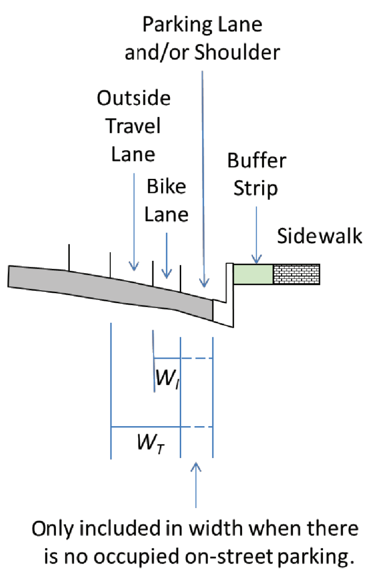
with

$$W_e = \begin{cases} W_v - 10p_{pk} \geq 0.0 & W_l < 4 \text{ feet} \\ W_v + W_l - 20p_{pk} \geq 0.0 & W_l \geq 4 \text{ feet} \end{cases} \tag{A14}$$

$$W_v = \begin{cases} W_T & v_m > 160 \text{ veh/h or roadway is otherwise divided} \\ W_T(2 - 0.005v_m) & \end{cases} \tag{A15}$$

where

W_e = effective width of the outside through lane (ft)
W_v = effective total width of outside through lane, bicycle lane, and shoulder as a function of traffic volume (ft)
W_l = width of bicycle lane and shoulder, from Figure A5 (ft)
W_T = total width of outside through lane, bicycle lane, and shoulder, from Figure A5 (ft)
v = average midblock volume in the direction of travel closest to the bicycle facility (veh/h)



Source: Adapted from *NCHRP Report 825*, Exhibit 102 (*2*).

Figure A5. Key dimensions used in determining bicycle LOS.

Equations A16 through A18, adapted from Equations 18-43 through 18-45, respectively, in the HCM6 (*1*), determine the motorized vehicle volume and speed adjustment factors and the pavement condition adjustment factor.

$$F_v = 0.507 \ln\left(\frac{v_m}{4N_{th}}\right) \tag{A16}$$

$$F_S = 0.199[1.1199 \ln(S_{Ra} - 20) + 0.8103](1 + 0.1038\, P_{HVa})^2 \tag{A17}$$

$$F_p = \frac{7.066}{P_C^2} \tag{A18}$$

where

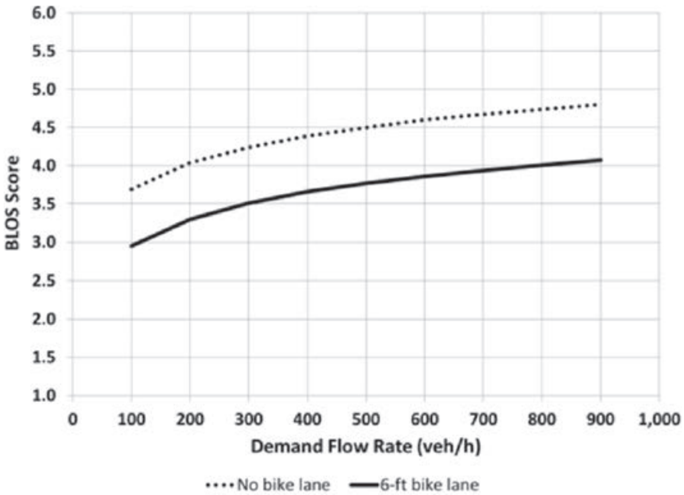
N_{th} = number of through lanes in the direction of travel of the bicycle facility
S_{Ra} = adjusted average motorized vehicle midblock running speed (mph) = max(21, S_R)
P_{HVa} = adjusted percent heavy vehicles = 50% if P_{HV} > 50% and v_m (1 – 0.01 P_{HV}) < 200 veh/h and = P_{HV} otherwise
P_{HV} = percent heavy vehicles
F_p = pavement condition adjustment factor
P_C = pavement condition (present serviceability) rating, from 0 (worst) to 5 (best)

Example 7. Assume that, as a result of an access management technique, average motorized vehicle midblock running speeds will increase by 2 mph, from 42 to 44 mph, and there are 5% trucks and buses in the traffic stream. From Equation A16, the before-and-after values of F_s are 1.96 and 2.01, respectively. Because nothing else changes that would affect BLOS, the BLOS value would go up (i.e., get worse) by 0.05 point as a result of the technique. The LOS letter would likely stay the same, as 0.05 is much less than the width of the range used to determine LOS letters (i.e., 1.00 point for links and 0.75 point for segments).

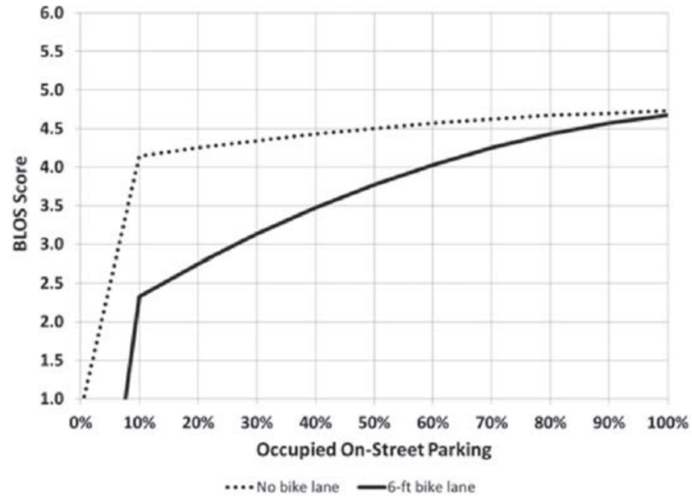
Example 8. Assume the roadway used in Example 3, with the following additional assumptions. They are 80% of the available parking is occupied on average, there is no bicycle lane, the parking lane width (not including the gutter) is 8 feet, the outside travel lane width is 12 feet, heavy vehicles form 5% of the traffic volume, and the pavement condition rating is 3. BLOS is then calculated as follows:

- *Cross-section adjustment factor.* Because the traffic volume is greater than 160 veh/h (as given in Example 3), $W_v = W_T$ = 12 feet (Equation A15) because there is no bicycle lane and because the parking lane width is not included in W_T when the lane is partially occupied with parked cars. Because there is no bicycle lane, $W_e = W_v$ = 12 feet (Equation A14). Then, from Equation A13, $F_w = -0.720$.
- *Motorized vehicle volume adjustment factor.* From Example 3, v_m = 1,087 veh/h and N_{th} = 2 lanes. Entering these values into Equation A16 gives a value of F_v of 2.490.
- *Motorized vehicle speed adjustment factor.* From Example 3, S_R = 33.0 mph. Applying Equation A17 gives a value for F_s of 1.691.
- *Pavement condition adjustment factor.* From Equation A18, F_p = 0.785.
- *Bicycle level of service score.* Entering the calculated adjustment factor values into Equation A12 gives a BLOS score of 5.01. From Table A5, this score for a link corresponds to LOS E.

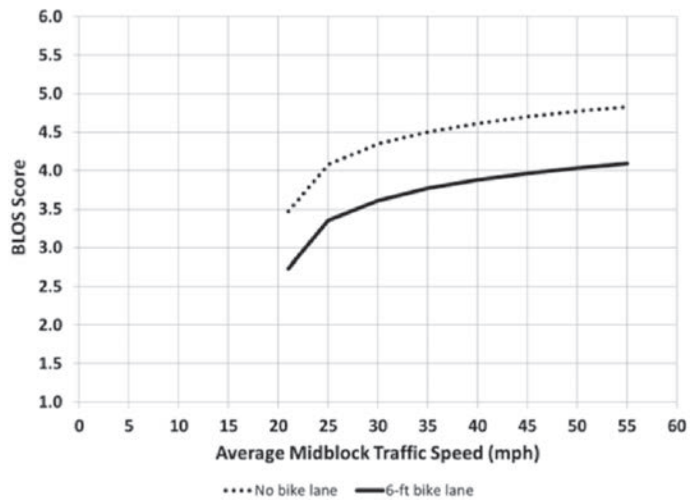
Figure A6 demonstrates the sensitivity of BLOS to various factors influenced by access management techniques.



(a)



(b)



(c)

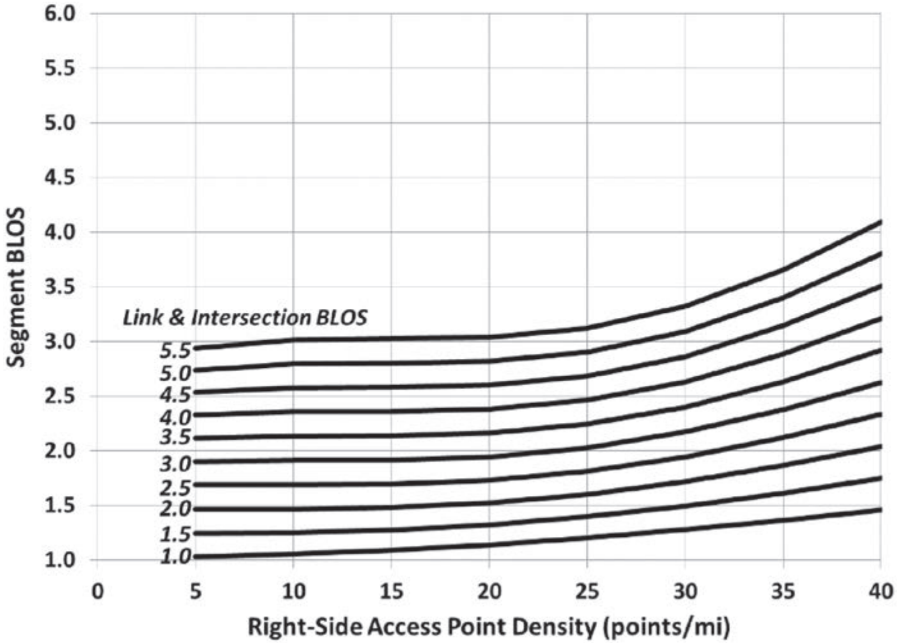
Note: Assumptions used in each graph are as follows:
(a) Outside lane demand flow rate = 500 vehicles per hour; no landscape buffer or street trees, outside travel lane width = 12 feet; parking lane width = 8 feet; and traffic speed = 35 mph.
(b) Occupied on-street parking = 50%; no landscape buffer or street trees, outside travel lane width = 12 feet; parking lane width = 8 feet; and traffic speed = 35 mph.
(c) Outside lane demand flow rate = 500 vehicles per hour; occupied on-street parking = 50%; no landscape buffer or street trees, outside travel lane width = 12 feet; and parking lane width = 8 feet.

Figure A6. Sensitivity of link BLOS to factors influenced by access management techniques: (a) traffic volume, (b) occupied on-street parking, and (c) average midblock traffic speed.

Segments

The number of access points per mile on the right side of the road is a factor in determining BLOS at the segment level. Equations 18-46 and 18-47 in the HCM6 can determine segment BLOS. Chapter 19 can estimate bicycle delay and BLOS at the traffic signal (*1*). These calculations may be easily done by using specialized HCM6-implementing software.

Figure A7 shows the sensitivity of segment BLOS to right-side access density for various levels of link BLOS, under the assumption that intersection BLOS (used in calculating segment BLOS) is equal to link BLOS.



Note: Assumptions used to develop the graph include link BLOS = intersection BLOS, segment length = ½ mile, average bicycle delay at the traffic signal at the end of the segment = 40 seconds, and average bicycle speed = 12 mph.

Figure A7. Sensitivity of segment BLOS to right-side access point density.

Transit LOS

Transit LOS (TLOS) for a roadway link is influenced by the bus frequency on the link, passengers' perceived travel time (primarily a function of bus speeds and loading), and the PLOS score for the link. The HCM6 method calculates a TLOS score, which translates into an LOS letter as shown in Table A6. Unlike the pedestrian and bicycle modes, TLOS is not computed at the link level but only at the segment level.

Equation A19, adapted from Equations 18-62 and 18-63 in the HCM6 (*1*), shows the component factors used to determine the TLOS score. A unit change in either the headway factor (not normally influenced by access management techniques) or the travel time factor changes the TLOS score by 1.5 units. Similarly, a unit change in the link PLOS changes the score by 0.15 units. If one knows these relationships, it is possible to determine the relative change in

Table A6. Transit LOS criteria.

LOS	TLOS Score
A	≤2.00
B	>2.00–2.75
C	>2.75–3.50
D	>3.50–4.25
E	>4.25–5.00
F	>5.00

Source: Derived from *Highway Capacity Manual*, 6th ed., Exhibit 18-3 (*1*).

TLOS due to particular access management techniques, without having to perform the full set of calculations.

$$\text{TLOS} = 6.0 - 1.50\, F_h F_{tt} + 0.15\, \text{PLOS}_l \tag{A19}$$

where

TLOS = transit LOS score for segment
F_h = headway factor
F_{tt} = perceived travel time factor
PLOS_l = pedestrian LOS score for link, from Equation A7

The headway and perceived travel time factors are determined as follows, adapted from Equations 18-56 through 18-60 in the HCM6 (*1*).

$$F_h = 4.00 e^{-1.434/(fb+0.001)} \tag{A20}$$

$$F_{tt} = \frac{(E-1)T_{btt} - (E+1)T_{ptt}}{(E-1)T_{ptt} - (E+1)T_{btt}} \tag{A21}$$

with

$$T_{ptt} = \left(a_1 \frac{60}{S_b}\right) + (2T_{ex}) - T_{at} \tag{A22}$$

$$a_1 = \begin{cases} 1.00 & F_l \le 0.80 \\ 1 + \dfrac{4(F_l - 0.80)}{4.2} & 0.80 \le F_l \le 1.00 \\ 1 + \dfrac{4(F_l - 0.80) + (F_l - 1.00)[6.5 + 5(F_l - 1.00)]}{4.2F_l} & F_l > 1.00 \end{cases} \tag{A23}$$

$$T_{at} = \frac{1.3 p_{sh} + 0.2 p_{be}}{L_{pt}} \tag{A24}$$

where

f_b = bus frequency stopping in or adjacent to segment (bus/h)
E = ridership elasticity with respect to changes in the travel time rate = −0.40
T_{btt} = base travel time rate (min/mi) = 6.0 for the central business district of a metropolitan area with 5 million persons or more; otherwise, $T_{btt} = 4.0$
T_{ptt} = perceived travel time rate (min/mi)
a_1 = perceived travel time weighting factor for passenger load
S_b = average bus speed (mph), including stops to serve passengers and traffic signal delay
T_{ex} = excess wait time rate (min/mi) = t_{ex}/L_{pt}
t_{ex} = excess passenger wait time due to late bus arrivals (min) (default = 3)
L_{pt} = average passenger trip length (mi) (default = 3.7)
T_{at} = amenity time rate (min/mi)
p_{sh} = proportion of stops in segment with shelters (decimal)
p_{be} = proportion of stops in segment with benches (decimal)

Increases in average midblock motor vehicle speeds produce much smaller increases in average bus speeds, when bus stop and traffic signal delays are considered. Buses spend relatively little time per mile traveling at a street's running speed, and much more time stopping to serve passengers (including time spent decelerating and accelerating back to running speed). On higher-speed roadways (e.g., 45 mph) with just 4 stops per mile buses cannot accelerate all the way to the posted speed before they have to begin decelerating for the next bus stop. Traffic signal delays are also a factor. Table A7 shows representative changes in average bus speeds resulting from a unit change in average midblock motorized vehicle speed. For example, on a street with a midblock running speed of 25 mph and 6 bus stops per mile, a 1-mph increase in motor vehicle running speeds would result in a 0.24-mph increase in average bus speeds.

Example 9. Assume that as a result of an access management technique average motorized vehicle midblock running speeds increase by 2 mph from 45 to 47 mph, average bus speeds are 17.1 mph, buses make 2 stops per mile along the roadway, a number of seats are usually available on the bus (load factor <0.80), and there are no shelters or benches at bus stops. From Table A7, average bus speeds would increase by (2 mph × 0.19) = 0.4 mph. There are no shelters or benches, therefore $T_{at} = 0$ min/mi (Equation A24). The perceived travel time weighting factor $a_1 = 0$, because the load factor is less than 0.80 (Equation A23). From Equation A21, the perceived travel time rate is 5.13 min/mi, which would drop to 5.05 min/mi following the implementation of the access management technique. These values are used in Equation A21, along with a base travel time rate of 4 min/mi and an elasticity value of –0.40 to obtain perceived travel time factors of 0.906 and 0.911 for the before-and-after-conditions, respectively. Finally, from Equation A19, the increase of 0.005 in the perceived travel time factor will result in a reduction (i.e., improvement) in the TLOS score of (0.005 × 1.5), which rounds to 0.01 point. In comparison, the range covered by one LOS letter is 0.75 point.

Example 10. Assume the roadway used in Example 6. Buses operate at 15-minute headways (i.e., 4 buses per hour) along the roadway. The scheduled bus travel speed is 12.5 mph, all seats on the bus are usually full during the peak hour (load factor = 1.00), and shelters and benches are provided at bus stops in this segment. From Equation A24, the amenity time rate $T_{at} = 0.41$ min/mi, assuming the default passenger trip length of 3.7 mi given with the equation. From Equation A23, $a_1 = 1.19$ for a load factor of 1.00. The perceived travel time rate is then 6.92 min/mi (Equation A22) and the travel time factor is 0.81 (Equation A21). From Equation A19, the headway factor is 2.80. Finally, from Example 6, the PLOS score for the link is 2.52. Entering these values into Equation A19 gives a TLOS score of 2.98, which corresponds to LOS C.

Table A7. Representative changes in average bus speed per unit change in midblock motorized vehicle running speeds.

Condition	Change
2 bus stops/mi, 45 mph	0.19
4 bus stops/mi, 35 mph	0.14
6 bus stops/mi, 35 mph	0.03
4 bus stops/mi, 30 mph	0.24
4 bus stops/mi, 25 mph	0.34
6 bus stops/mi, 25 mph	0.24

Source: Calculated from data in the *Transit Capacity and Quality of Service Manual* (*4*).

Pedestrian and Bicycle Delay Methods in the HCM6

Pedestrian Delay

Chapter 19 in the HCM6 provides Equation 19-70 (*1*) for estimating average pedestrian delay crossing one crosswalk at a traffic signal, assuming random pedestrian arrivals at the crosswalk:

$$d_p = \frac{(C - g_{\text{walk}})^2}{2C} \tag{A25}$$

where

d_p = average pedestrian delay (s)
C = traffic signal cycle length (s)
g_{walk} = effective walk time for the crosswalk (typically the walk time plus 4 s). See HCM6 page 19-78 for additional guidance.

Access management techniques that result in a wider intersection that in turn requires a longer cycle time to accommodate the increased pedestrian crossing distance may affect pedestrian delay at signalized pedestrian crossings.

At unsignalized crosswalks, access management techniques that shorten the crossing distance or split the crossing into two stages (e.g., by installing a non-traversable median) or that increase the crossing distance (e.g., by widening the roadway to add a right-turn lane) will affect pedestrian delay. The pedestrian method provided in Chapter 20 in the HCM6 allows the delay to be calculated and includes consideration of driver-yielding behavior (*1*). The method is too involved to describe in this report but can be readily input into a spreadsheet or applied by using specialized HCM6-implementing software. Required input data for the method include crosswalk length, median presence, roadway speed limit, vehicular flow rate, and average pedestrian speed.

Bicycle Delay

Chapter 19 in the HCM6 provides Equation 19-78 (*1*) for estimating average bicycle delay at a traffic signal:

$$d_b = \frac{0.5C(1 - g_b/C)^2}{1 - \min\left(\frac{v_b}{c_b}, 1.0\right)\frac{g_b}{C}} \tag{A26}$$

where

d_b = average bicycle delay (s)
g_b = effective green time for bicyclists (typically the same as for motor vehicles, unless bicycle signals are used)
v_b = bicycle demand flow rate (bicycles/h)
c_b = bicycle capacity (bicycles/h) = 2,000 (g_b/C)

As is the case with pedestrian delay, access management techniques that result in a longer traffic signal cycle length being required can have an effect on bicycle delay.

The HCM6 does not provide a bicycle delay method for unsignalized intersections, but Chapter 20 does reference a limited set of literature on the topic (*1*).

Truck Level of Service

Section P in Exhibit 3 of *NCHRP Report 825* (*2*) describes the use of a truck LOS measure developed in *NCFRP Report 31* (*5*). Truck LOS is "a measure of the quality of service provided by a facility for truck hauling of freight as perceived by shippers and carriers. It is measured in terms of the percentage of ideal conditions achieved by the facility for truck operations" (*2*). Factors determining "ideal conditions" consist of "a facility usable by trucks with legal size and weight loads, with no at-grade railroad crossings, that provides reliable truck travel at truck free-flow speeds, at low cost (i.e., no tolls)" (*2*).

Equations A27 and A28, which are based on Equations 192 and 193 in *NCHRP Report 825* (*2*), calculate a truck LOS index:

$$\%\text{TKLOS} = \frac{1}{\left(1 + 0.10e^{-200U(x)}\right)} \quad \text{(A27)}$$

$$U(x) = A \times (\text{POTA} - 1) + B \times (\text{TTI} - 1) + C \times (\text{TOLL}) + D \times (\text{TFI} - 1) \quad \text{(A28)}$$

where

%TKLOS = truck LOS index as a percentage of ideal conditions (decimal)
$U(x)$ = utility of facility for truck shipments
A = weighting parameter for reliability, sensitive to shipping distance = 5/ASL, where ASL = average shipment length (mi) = 200 (lower 48 states), 280 (Alaska), or 30 (Hawaii)
POTA = probability of on-time arrival = 1 if TTI_{mix} is ≤ 1.33 (freeways and highways) or ≤ 3.33 (urban streets), where TTI_{mix} = mixed flow (auto and truck) travel time index, the ratio of FFS to actual speed
B = weighting parameter for shipment time, sensitive to free-flow speed = –0.32/FFS, where FFS = truck free-flow speed (mph)
TTI = truck travel time index for the study period, the ratio of truck free-flow speed to actual truck speed
C = weighting parameter for shipment cost = –0.01
TOLL = truck toll rate ($/mile), a truck volume–weighted average for all truck types
D = weighting parameter for the facility's truck friendliness = 0.03
TFI = truck friendliness index, ranging from 1.00 (no constraints or obstacles to legal truck load and vehicle usage of facility) to 0.00 (no trucks may use facility)

The value of TFI can be reduced below 1.00 to reflect sub-optimal conditions for trucks (e.g., weight restrictions or railroad grade crossings). *NCFRP Report 31* provides guidance (*5*). The utility equation is weighted so a TFI of 0.60 or less will always result in truck LOS F.

Equations A29 and A30, which are based on Equations 195 and 196 in *NCHRP Report 825* (*2*), are used to determine the 95th percentile truck travel time index. The 95th percentile truck TTI is used in Table A8 to estimate the probability of on-time arrival, interpolating as necessary.

$$\text{TTI} = \text{TTI}_{mix} \times f_{LA} \quad \text{(A29)}$$

$$\text{TTI}_{95} = 1 + 3.67 \times \ln(\text{TTI}) \quad \text{(A30)}$$

Table A8. Look-up table for probability of on-time arrival.

Truck TTI	95% Truck TTI	Probability of On-Time Arrival (%)
1.20	1.67	100.00
1.40	2.23	99.89
1.60	2.72	98.93
1.80	3.16	96.51
2.00	3.54	92.67
2.20	3.89	87.70
2.40	4.21	81.91

Source: NCHRP Report 825, Exhibit 119 (*2*).

where

f_{LA} = local adjustment factor to account for local truck driving behavior (decimal) (default = 1.00)
TTI_{95} = 95th percentile truck LOS index

The mixed-flow free-flow speed and average travel speed can be estimated by using HCM6 methods, as described earlier in the appendix. The local adjustment factor can be set to a value less than 1.00 when truck free-flow speeds are significantly below auto speeds (e.g., extended upgrades or downgrades or situations when the truck speed limit is lower than the auto speed limit and trucks comply).

Once the probability of on-time arrival is determined, all of the information needed to calculate the facility utility and truck LOS index is available. If desired, the truck LOS index can be converted into a LOS letter, as shown in Table A9. A computational engine (spreadsheet) for calculating truck LOS is available in the Application Guides section of the HCM Volume 4 website (hcmvolume4.org).

Example 11. An urban arterial has a mixed-flow free-flow speed of 36.5 mph, an average travel speed of 25.0 mph, and trucks are capable of traveling at the same speed as auto traffic (i.e., $f_{LA} = 1.00$). Any truck with a legal load and dimensions can use the roadway. The road has no tolls and no railroad grade crossings. The mixed-flow TTI is (36.5/25.0) = 1.46, and the truck TTI equals the mixed-flow TTI, from Equation A29. The 95th percentile truck TTI is 2.39, from Equation A30. By interpolation in Table A8, the probability of on-time arrival is 99.58%. Next, from Equation A28, the facility's utility is –0.0041. Finally, from Equation A27, the truck LOS index is 81%, which corresponds to LOS B for an urban principal arterial (Class II, secondary facility) using Table A9.

Table A9. Truck LOS criteria.

LOS	Class I Primary Freight Facility (%)	Class II Secondary Facility (%)	Class III Tertiary Facility (%)
A	≥ 90	≥ 85	≥ 80
B	≥ 80	≥ 75	≥ 70
C	≥ 70	≥ 65	≥ 60
D	≥ 60	≥ 55	≥ 50
E	≥ 50	≥ 45	≥ 40
F	< 50	< 45	< 40

Note: Class I facilities include interstate highways and interregional rural principal arterials.
Class II facilities include urban principal arterials and connectors to major intermodal facilities.
Class III facilities include access roads to industrial areas, truck terminals, and truck stops.
Source: NCHRP Report 825, Exhibit 117 (*2*).

Crash Modification Factors

Crash modification factors are tools for estimating the effect of selected access management techniques on a roadway's crash rate. They can be applied directly to a known, long-term (e.g., 5 years or more) crash history for a roadway to estimate the change in crash rate that would occur from implementing the technique. However, this approach is susceptible to regression-to-the-mean bias, in which the number of crashes during the study period happens to be higher or lower than the site's true long-term average. To address this issue, the *Highway Safety Manual*, 1st ed., recommends using, where possible, the Empirical Bayes method. This method combines a site's observed crash history with the predicted number of crashes for the site, based on data from other similar sites that have been incorporated into a safety performance function (SPF) for a roadway or intersection (*6*, *7*).

Two sources of CMFs are the HSM (*7*) and FHWA's CMF Clearinghouse. CMFs from the HSM that are relevant to access management techniques are in the body of the guide. Newer CMFs may be available through the CMF Clearinghouse, which rates the quality of each CMF on a 5-star scale, based on the underlying study's design, sample size, standard error, potential study bias, and data source (*8*). Analysts should evaluate both the overall quality of CMFs obtained from the CMF Clearinghouse and their suitability to their study site (e.g., similar site characteristics or similar crash characteristics). The CMF Clearinghouse provides links to numerous resources on best practices for applying CMFs to safety analyses.

Chapter 12 of the HSM (*7*) provides SPFs applicable to the following types of urban and suburban arterials:

- 2- and 4-lane undivided arterials
- 4-lane divided arterials
- 3- and 5-lane arterials with two-way left-turn lanes

The SPF for predicting multiple-vehicle driveway-related crashes considers the number of driveways along a section of arterial, the volume of those driveways (major or minor), and the land use served by the driveway. Other SPFs, including those for predicting pedestrian and bicycle crashes, are not directly sensitive to access management techniques (except through the application of CMFs) but may be indirectly affected by changes in annual average daily traffic volumes that result from certain techniques.

Bowman et al. Vehicle and Pedestrian Crash Models by Median Type

Bowman et al. (*9*) studied the vehicle and pedestrian crash histories of 45 urban and suburban arterials evenly divided between the Atlanta, Phoenix, and Los Angeles regions. The authors developed six crash prediction models, one for each combination of vehicle–vehicle and vehicle–pedestrian crashes along undivided roadways, roadways with a raised median, and roadways with a two-way left-turn lane.

The models are negative binomial models with the general form of

$$\mathrm{CR} = e^{(a + b_1 x_1 + \cdots + b_i x_i)} \quad \text{(A31)}$$

where

CR = crash rate (crashes/100 million vehicle miles)
a = model constant
b_i = model coefficient for independent variable i
x_i = value of independent variable i

Table A10. Crash prediction model coefficients.

Independent Variable	Vehicle–Vehicle			Vehicle–Pedestrian		
	Raised Median	TWLTL	Undivided	Raised Median	TWLTL	Undivided
Constant	7.20515	3.70539	1.88309	−0.88369	−0.97281	−1.10911
Accident reporting threshold ($)	−0.00788	−0.00278	−0.003031	—	—	—
Land use type = office (1 = yes, 0 = no)	−0.44812	0.07227	1.06414	−1.65869	—	0.55689
Land use type = business (1 = yes, 0 = no)	—	—	0.65731	—	—	0.73696
Area type (1 = central business district, 0 = suburban)	—	—	0.45652	1.03664	0.95036	1.43794
Number of lanes, excluding TWLTL	—	—	—	—	—	−0.25583
Median width (ft)	−0.02755	0.03544	—	−0.07866	−0.077121	—
Number of minor crossroads per mile	—	−0.06057	—	—	—	—
Number of driveways per mile	—	0.01294	0.01324	0.02163	—	—
Number of crossovers per mile	0.09615	—	—	—	—	—
Posted speed limit (mph)	−0.07002	−0.03389	—	−0.03922	—	—

Note: A dash indicates a variable is not included in the model for this combination of crash type and median type.
Source: Bowman et al., Table 3 (*9*).

Table A10 provides the model coefficients for each combination of crash type and median type.

The models are only applicable to urban and suburban arterials with characteristics within the range indicated in Table A11. The vehicle–vehicle TWLTL model has the best fit, while the vehicle–pedestrian models predict crash rate less accurately than the vehicle–vehicle models. In particular, the pedestrian models tend to underestimate the crash rate, particularly for roadways with TWLTLs. The authors also noted that the models indicate that the crash rate decreases as the posted speed increases and attributed this result to the fact that "higher speeds . . . usually occur where development intensity, and hence vehicle interactions are less, thereby, resulting in lower accident frequency."

Example 12. A suburban arterial in an area with strip commercial land use has a 14-foot-wide TWLTL, a 35-mph posted speed, 30 driveways per mile, and 6 minor crossroads per mile. The crash-reporting threshold in this jurisdiction is $500. How might the vehicle–pedestrian and vehicle–vehicle crash rates change with the installation of a 14-foot raised median providing 6 crossovers per mile?

Table A11. Ranges of independent variables used in developing Bowman et al. models.

Independent Variable	Independent Variable Range	
	Minimum	Maximum
Average daily traffic (veh/day)	11,500	60,000
Arterial length (mi)	0.5	5.6
Driveways per mile	4.3	90.0
Minor crossroads per mile	0.0	20.0
Crossovers per mile (raised medians only)	4.3	11.0
Median width (ft) (raised median)	3.0	40.0
Median width (ft) (TWLTL)	10.0	12.0
Traffic signals per mile	1.0	20.0
Posted speed limit (mph)	25.0	55.0
Number of lanes	2	6

Source: Bowman et al., Table 4 (*9*).

The predicted vehicle–pedestrian crash rate for the existing roadway is

$$CR = e^{(-0.97281+(0.95036)(0)-(0.077121)(14))} = 0.13 \text{ crashes/100 million vehicle miles}$$

while the predicted vehicle–pedestrian crash rate with a median is

$$CR = e^{(-0.88369-(1.65869)(0)+(1.03664)(0)-(0.07866)(14)+(0.02163)(30)-(0.03922)(35))} = 0.067$$

Similarly, the predicted vehicle–vehicle crash rate for the existing roadway is 5.2 crashes per 100 million vehicle miles, compared with 2.7 with the median.

Potts et al. Pedestrian Crash Model for Right-Turn Lanes

Potts et al. (*10*) studied the vehicle and pedestrian crash histories of 103 four-leg signalized intersections in Toronto, Canada. In general, they found no significant difference in vehicle–vehicle crashes when comparing channelized right-turn lanes with unchannelized right-turn lanes and no turn lanes. In a related case, a model addressing merging crashes on the cross street, the overall model showed channelized right turns had a lower crash rate than unchannelized right-turn lanes but a higher crash rate than with no turn lanes, but comparisons between the individual right-turn treatments showed no significant differences. However, a model of vehicle–pedestrian crashes showed that the crash rate for unchannelized right-turn lanes was significantly higher than for channelized right turns or no turn lanes.

Equation A32 shows the model form as follows:

$$N_{ped} = e^{(-12.13+(0.02)(STR)+(0.57)(RTL)+(0.71)\ln(VOL1)+(0.50)\ln(VOL3))} \quad (A32)$$

where

N_{ped} = predicted number of pedestrian crashes per year per approach
STR = dummy variable for shared through/right lane = 1 if present; 0 otherwise
RTL = dummy variable for unchannelized right-turn lane = 1 if present; 0 otherwise
VOL1 = daily right-turning motor vehicle volume on the approach (veh/day)
VOL3 = daily pedestrian volume on the two crosswalks conflicting with the right-turn movement (ped/day).

Example 13. A right-turn lane is under consideration to be added at a signalized intersection. The average daily right-turning volume on the approach is 1,700 vehicles per day, while the total average daily pedestrian volume on the crosswalks crossed by the right-turn movement is 400 pedestrians per day. What is the predicted number of vehicle–pedestrian crashes for each type of right-turn treatment, no right-turn lane, unchannelized right-turn lane, and channelized right-turn lane?

Applying Equation A32 to the situation without a right-turn lane gives the following:

$$N_{ped} = e^{(-12.13+(0.02)(1)+(0.57)(0)+(0.71)\ln(1{,}700)+(0.50)\ln(400))} = 0.022 \text{ crash/year}$$

Similarly, the number of predicted crashes with an unchannelized right-turn lane is 0.038 crash/year and the number of predicted crashes with a channelized right-turn lane is 0.021 crash/year.

Carter et al. Pedestrian and Bicycle Intersection Safety Indices

Carter et al. (*11, 12*) developed safety indices that predict the safety ratings that pedestrians and bicyclists would give crossing and turning movements at intersections. Unlike other safety models presented earlier in the appendix, these indices do not predict crashes or crash rates. Rather, the indices prioritize locations for safety improvements and compare the relative safety ratings resulting from alternative improvement options. The pedestrian intersection safety index (ISI) can be applied to individual crosswalks at an intersection. The three bicycle ISIs are applied to the through, right-turn, and left-turn movements, respectively, on an intersection approach.

The basis for the indices is a regression model that relates the ratings that expert panels (one for the pedestrian model and one for the bicycle models) gave to video clips to the conditions existing at the intersections shown in the video clips. However, the indices also incorporate variables found to be significant in a separate behavioral model, in which conflicts and avoidance maneuvers between vehicles and pedestrians and vehicles and bicyclists were observed and recorded. The video clips used for the pedestrian model included 68 intersection approaches in San Jose, California; Miami–Dade County, Florida; and Philadelphia, Pennsylvania. The video clips used for the bicycle models came from 67 intersection approaches in Gainesville, Florida; Eugene, Oregon; Portland, Oregon; and Philadelphia, Pennsylvania.

Pedestrian Intersection Safety Index

The pedestrian ISI is determined from Equation A33 as follows:

$$\begin{aligned} ISI_{ped} = {} & 2.372 - 1.867(\text{Signal}) - 1.807(\text{Stop}) + 0.335(\text{ThruLanes}) + 0.018(\text{Speed}) \\ & + 0.006(\text{MainADT} \times \text{Signal}) + 0.238(\text{Commercial}) \end{aligned} \quad \text{(A33)}$$

where

ISI_{ped} = pedestrian intersection safety index (1 = best, 6 = worst)
Signal = dummy variable for traffic signal–controlled crossing (1 = yes, 0 = no)
Stop = dummy variable for stop sign–controlled crossing (1 = yes, 0 = no)
ThruLanes = number of through lanes on street being crossed (both directions)
Speed = 85th percentile speed of street being crossed (mph)
MainADT = average daily traffic volume on street being crossed, in thousands (1,000 veh/day)
Commercial = dummy variable for commercial land use (e.g., retail, restaurants) being predominant in the area surrounding the crossing (1 = yes, 0 = no)

The variables in the pedestrian ISI are not directly affected by access management techniques. However, both traffic speed and volume may be indirectly affected by some techniques. The model indicates that the pedestrian ISI worsens by 0.018 rating points for each 1 mph increase in traffic speeds on the street being crossed and by 0.006 points for each 1,000 increase in daily traffic volume on the street being crossed when the crossing is signalized. The "main street" for the pedestrian ISI is the street being crossed, while the "main street" for the bicycle ISI is the street on which the intersection approach of interest is located.

Bicycle Intersection Safety Indices

The bicycle ISIs are determined for each possible bicycle movement from an approach and are given by Equations A34 through A36:

$$
\begin{aligned}
ISI_{bike,th} = {} & 1.13 + 0.019(MainADT) + 0.815(MainHiSpeed) + 0.650(TurnVeh) \\
& + 0.470(RTLanes \times BikeLane) + 0.023(CrossADT \times NoBikeLane) \\
& + 0.428(Signal \times NoBikeLane) + 0.200(Parking)
\end{aligned}
\qquad (A34)
$$

$$
\begin{aligned}
ISI_{bike,rt} = {} & 1.02 + 0.027(MainADT) + 0.519(RTCross) + 0.151(CrossLanes) \\
& + 0.200(Parking)
\end{aligned}
\qquad (A35)
$$

$$
\begin{aligned}
ISI_{bike,lt} = {} & 1.10 + 0.025(MainADT) + 0.836(BikeLane) + 0.485(Signal) \\
& + 0.736(MainHiSpeed \times BikeLane) + 0.380(LTCross \times NoBikeLane) \\
& + 0.200(Parking)
\end{aligned}
\qquad (A36)
$$

where

$ISI_{bike,th}$ = bicycle intersection safety index for the through movement (1 = best, 6 = worst)
$ISI_{bike,rt}$ = bicycle intersection safety index for the right-turn movement (1 = best, 6 = worst)
$ISI_{bike,lt}$ = bicycle intersection safety index for the left-turn movement (1 = best, 6 = worst)
MainADT = average daily traffic volume on the main street, in thousands (1,000 veh/day)
MainHiSpeed = dummy variable for main street speed limit ≥35 mph (1 = yes, 0 = no)
TurnVeh = dummy variable for presence of turning-vehicle traffic across the path of bicyclists at the intersection (1 = yes, 0 = no) (e.g., dummy variable is no with a bike-lane crossover of a right-turn lane or where right turns are prohibited)
RTLanes = number of right-turn lanes on the main street approach (0, 1, or 2)
BikeLane = dummy variable for the presence of a bike lane or bike-lane crossover (1 = yes, 0 = no)
CrossADT = average daily traffic volume on the cross street, in thousands (1,000 veh/day)
NoBikeLane = dummy variable for the absence of a bike lane or bike-lane crossover (1 = yes, 0 = no)
Signal = dummy variable for traffic signal at intersection (1 = yes, 0 = no)
Parking = dummy variable for on-street parking on the main street approach (1 = yes, 0 = no)
RTCross = number of traffic lanes for cyclists to cross or enter to make a right turn (assumes the bicyclist is riding in a right- or left-side bicycle lane or on the right side of the street)
CrossLanes = number of through lanes on the cross street
LTCross = number of traffic lanes for cyclists to cross or enter to make a left turn (assumes the bicyclist is riding in a right- or left-side bicycle lane or on the right side of the street and does not make a two-stage left turn)

The combination of a right-turn lane and a bicycle lane, where right-turning traffic crosses over the bicycle lane, makes the through-movement bicycle ISI worse by 0.47 rating points. Traffic signals make the through-movement bicycle ISI worse by 0.428 points when there is no bicycle lane and make the left-turn bicycle ISI worse by 0.485 points. Removing on-street parking on the intersection approach improves the bicycle ISI for all movements by 0.2 points. Access management techniques are unlikely to affect the other bicycle ISI components except they may indirectly affect the ones related to traffic volume.

Carter et al. (*11*) noted that the following conditions appeared to result in lower survey ratings than predicted by the model; however, because these conditions appeared in only one or a few videos, the conditions were not able to be modeled. They are

- Slip lane or channelized right-turn lane
- Pavement irregularities (e.g., broken asphalt, tracks, gutters, or grates)
- High crossing pedestrian volumes
- Vehicles stopped in the bicycle travel space to load or unload
- Bicycle lane to the right of an exclusive right-turn lane
- Perpendicular on-street parking
- Buses entering or exiting an area where they can potentially interact with bicyclists
- Offset intersections
- Parking dimensions (e.g., width of parallel parking spaces or bike lane proximity to parking)

References

1. *Highway Capacity Manual: A Guide for Multimodal Mobility Analysis,* 6th ed. Transportation Research Board, Washington, D.C., 2016.
2. Dowling, R., P. Ryus, B. Schroeder, M. Kyte, T. Creasey, N. Rouphail, A. Hajbabaie, and D. Rhoades. *NCHRP Report 825: Planning and Preliminary Engineering Applications Guide to the* Highway Capacity Manual. Transportation Research Board, Washington, D.C., 2016.
3. Bonneson, J. A., M. P. Pratt, and M. A. Vandehey. *Predicting the Performance of Automobile Traffic on Urban Streets: Final Report*. NCHRP Project 03-79. Transportation Research Board of the National Academies, Washington, D.C., Jan. 2008.
4. Kittelson & Associates, Inc.; Parsons Brinckerhoff; KFH Group, Inc.; Texas A&M Transportation Institute; and Arup. *TCRP Report 165: Transit Capacity and Quality of Service Manual,* 3rd ed. Transportation Research Board of the National Academies, Washington, D.C., 2013.
5. Dowling, R., G. List, B. Yang, E. Witzke, and A. Flannery. *NCFRP Report 31: Incorporating Truck Analysis into the Highway Capacity Manual*. Transportation Research Board of the National Academies, Washington, D.C., 2014.
6. Federal Highway Administration. *Crash Modification Factors in Practice: Quantifying Safety in the Roadway Safety Management Process.* Publication FHWA-SA-13-010. Federal Highway Administration, Washington, D.C., 2013.
7. *Highway Safety Manual,* 1st ed. American Association of State Highway and Transportation Officials, Washington, D.C., 2010.
8. About the Star Quality Rating. Crash Modification Factor Clearinghouse. http://www.cmfclearinghouse.org/sqr.cfm. Accessed Oct. 2, 2017.
9. Bowman, B., R. Vecellio, and J. Miao. Vehicle and Pedestrian Accident Models for Median Locations. *Journal of Transportation Engineering,* Vol. 121, No. 6, American Society of Civil Engineers, Washington, D.C., Nov.–Dec. 1994, pp. 531–537.
10. Potts, I. B., D. W. Harwood, K. M. Bauer, D. K. Gilmore, J. M. Hutton, D. J. Torbic, J. F. Ringert, A. Daleiden, and J. M. Barlow. *NCHRP Web-Only Document 208: Design Guidance for Channelized Right-Turn Lanes.* Transportation Research Board of the National Academies, Washington, D.C., July 2011.
11. Carter, D. L., W. W. Hunter, C. V. Zegeer, J. R. Stewart, and H. F. Huang. *Pedestrian and Bicyclist Intersection Safety Indices: Final Report.* Report FHWA-HRT-06-125. Federal Highway Administration, Washington, D.C., Nov. 2006.
12. Carter, D. L., W. W. Hunter, C. V. Zegeer, J. R. Stewart, and H. F. Huang. *Pedestrian and Bicyclist Intersection Safety Indices: User Guide.* Report FHWA-HRT-06-130. Federal Highway Administration, Washington, D.C., April 2007.

Abbreviations and acronyms used without definitions in TRB publications:

A4A	Airlines for America
AAAE	American Association of Airport Executives
AASHO	American Association of State Highway Officials
AASHTO	American Association of State Highway and Transportation Officials
ACI–NA	Airports Council International–North America
ACRP	Airport Cooperative Research Program
ADA	Americans with Disabilities Act
APTA	American Public Transportation Association
ASCE	American Society of Civil Engineers
ASME	American Society of Mechanical Engineers
ASTM	American Society for Testing and Materials
ATA	American Trucking Associations
CTAA	Community Transportation Association of America
CTBSSP	Commercial Truck and Bus Safety Synthesis Program
DHS	Department of Homeland Security
DOE	Department of Energy
EPA	Environmental Protection Agency
FAA	Federal Aviation Administration
FAST	Fixing America's Surface Transportation Act (2015)
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
HMCRP	Hazardous Materials Cooperative Research Program
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
MAP-21	Moving Ahead for Progress in the 21st Century Act (2012)
NASA	National Aeronautics and Space Administration
NASAO	National Association of State Aviation Officials
NCFRP	National Cooperative Freight Research Program
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
NTSB	National Transportation Safety Board
PHMSA	Pipeline and Hazardous Materials Safety Administration
RITA	Research and Innovative Technology Administration
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
TDC	Transit Development Corporation
TEA-21	Transportation Equity Act for the 21st Century (1998)
TRB	Transportation Research Board
TSA	Transportation Security Administration
U.S. DOT	United States Department of Transportation

TRANSPORTATION RESEARCH BOARD
500 Fifth Street, NW
Washington, DC 20001

ADDRESS SERVICE REQUESTED

NON-PROFIT ORG.
U.S. POSTAGE
PAID
COLUMBIA, MD
PERMIT NO. 88

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

The nation turns to the National Academies of Sciences, Engineering, and Medicine for independent, objective advice on issues that affect people's lives worldwide.
www.national-academies.org

ISBN 978-0-309-48003-1
90000
9 780309 480031