NCHRP

REPORT 600A

NATIONAL
COOPERATIVE
HIGHWAY
RESEARCH
PROGRAM

Human Factors Guidelines for Road Systems

Collection A: Chapters 1, 2, 3, 4, 5, 10, 11, 13, 22, 23, 26

TRANSPORTATION RESEARCH BOARD
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NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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John L. Campbell
Christian M. Richard
BATTELLE
Seattle, WA

Jerry Graham
MIDWEST RESEARCH INSTITUTE
Kansas City, MO

Subject Areas
Safety and Human Performance

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

TRANSPORTATION RESEARCH BOARD
WASHINGTON, D.C.
2008
www.TRB.org

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM

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

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The needs for highway research are many, and the National Cooperative Highway Research Program can make significant contributions to the solution of 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 REPORT 600A

Project 17-31
ISSN 0077-5614
ISBN 978-0-309-09919-6
Library of Congress Control Number 2008900429

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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 at:

http://www.national-academies.org/trb/bookstore

Printed in the United States of America

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FOREWORD

By Charles W. Niessner
Staff Officer
Transportation Research Board

This report contains guidelines that provide human factors principles and findings for consideration by highway designers and traffic engineers. The guidelines allow the non-expert in human factors to more effectively consider the roadway user's capabilities and limitations in the design and operation of highway facilities.

The TRB, AASHTO, and the FHWA have been working since 2001 on two projects that together will help to promote greater safety for all road users. These two projects are the *Highway Safety Manual* (HSM) and the *Human Factors Guidelines for Road Systems* (HFG). These projects have been supported by funding from NCHRP and the FHWA. The TRB supports the *Highway Safety Manual* through the HSM Task Force and the *Human Factors Guidelines for Road Systems* through the Joint Subcommittee for the Development of a Human Factors Guideline for Road Systems.

The HSM and HFG promote improved safety for highway users and complement each other. They should be used together. Neither document is a substitute for national or state standards such as AASHTO's *A Policy on Geometric Design of Highways and Streets* or the *Manual on Uniform Traffic Control Devices*.

The HSM provides highway engineers with a synthesis of validated highway research and proven procedures for integrating safety into both new and improvement projects. It also provides practitioners with enhanced analytic tools for predicting and measuring the success of implemented safety countermeasures.

After using the HSM to develop possible design alternatives to improve safety on an in-service or planned intersection or section of roadway, the practitioner may then use the HFG to enhance the possible solutions. Successful highway safety depends on the consideration and integration of three fundamental components—the roadway, the vehicle, and the roadway user. Unfortunately, the information needs, limitations, and capabilities of roadway users are lacking in many traditional resources used by practitioners. The easy-to-use guidelines in the HFG provide the highway designer and traffic engineer with objective, defensible human factors principles and information that can be used to support and justify design decisions. The HFG will allow the non-expert in human factors to recognize the needs and limitations of the road user in a more effective manner and design roads that are safer for all.

When reviewing either existing or planned roads or intersections, highway designers and traffic engineers are strongly encouraged to use both the HFG and the HSM to identify and develop the safest solutions for road users.

NOTES ON PUBLICATION OF *HUMAN FACTORS GUIDELINES FOR ROAD SYSTEMS*

Chapters 1 through 5, 10, 11, 13, 22, 23, and 26 are contained herein. Chapter 6 is expected late 2008/early 2009. Additional chapters will be developed under NCHRP Project 17-41 according to the priorities established by the project panel and are expected in late 2010. One additional project will most likely be needed to complete the guidelines. The problem statement for this final contract will be submitted to the AASHTO Standing Committee on Research for consideration at its March 2009 meeting.

Chapter 3 (Finding Information Like a Road User) and Chapter 4 (Integrating Road User, Highway Design, and Traffic Engineering Needs) are authored by Samuel Tignor, Thomas Hicks, and Joseph Mondillo.

Chapter 5 (Sight Distance Guidelines) and Tutorials 1 and 2 in Chapter 22 (Tutorials) present a revision of materials originally published as: Lerner, N., Llaneras, R., Smiley, A., and Hanscom, F. (2004). *NCHRP Web-Only Document 70: Comprehensive Human Factors Guidelines for Road Systems.* Washington, DC: Transportation Research Board.

Chapter locations and publication dates.

Chapter	Published in Report	Publication Date
1. Why Have Human Factors Guidelines for Road Systems?	600A	March 2008
2. How to Use this Document	600A	March 2008
3. Finding Information Like a Road User	600A	March 2008
4. Integrating Road User, Highway Design, and Traffic Engineering Needs	600A	March 2008
5. Sight Distance Guidelines	600A	March 2008
6. Curves (Horizontal Alignment)		Forthcoming
7. Grades (Vertical Alignment)		Forthcoming
8. Tangent Sections and Roadside (Cross Section)		Forthcoming
9. Transition Zones Between Varying Road Designs		Forthcoming
10. Non-Signalized Intersections	600A	March 2008
11. Signalized Intersections	600A	March 2008
12. Interchanges		Forthcoming
13. Construction and Work Zones	600A	March 2008
14. Rail-Highway Grade Crossings		Forthcoming
15. Special Considerations for Urban Environments		Forthcoming
16. Special Considerations for Rural Environments		Forthcoming
17. Speed Perception, Speed Choice, and Speed Control		Forthcoming
18. Signing		Forthcoming
19. Variable Message Signs		Forthcoming
20. Markings		Forthcoming
21. Lighting		Forthcoming
22. Tutorials	600A	March 2008
23. References	600A	March 2008
24. Glossary		Forthcoming
25. Index		Forthcoming
26. Abbreviations	600A	March 2008
27. Equations		Forthcoming

All published chapters are available as individual PDF files and as a consolidated PDF file on the TRB website (www.trb.org/news/blurb_detail.asp?id=8715).

CONTENTS*

* See "Notes on Publication of *Human Factors Guidelines for Road Systems*" on facing page.

PART III Human Factors Guidance for Roadway Location Elements

PART I

Introduction

CHAPTER 1

Why Have Human Factors Guidelines for Road Systems?

1.1 Purpose of Human Factors Guidelines for Road Systems

The purpose of *Human Factors Guidelines for Road Systems* (HFG) is to provide the best factual information and insight on the characteristics of road users to facilitate safe roadway design and operational decisions.

A number of existing guides, standards, and references are available to facilitate safe roadway design and operational decisions, including *A Policy on Geometric Design of Highways and Streets* (AASHTO, 2004), the *Manual on Uniform Traffic Control Devices* (MUTCD) (FHWA, 2003), and the forthcoming *Highway Safety Manual* (HSM) (see Hughes, Eccles, Harwood, Potts & Hauer, 2004). However, these materials often lack a substantive presentation and discussion of human factor principles and concepts that could be used by highway designers and traffic engineers to improve roadway design and traffic safety. Despite a widespread acknowledgement that traffic safety reflects the consideration and integration of three components—the roadway, the vehicle, and the roadway user—the information needs, limitations, and capabilities of roadway users are often neglected in traditional resources used by practitioners. In short, existing references applicable to road system design do not provide highway designers and traffic engineers with adequate guidance for incorporating road user needs, limitations, and capabilities when dealing with design and operational issues.

The *Human Factors Guidelines for Road Systems* is intended to provide human factors principles and findings to the highway designer and traffic engineer. It will allow the non-expert in human factors to more effectively bring consideration of the road user's capabilities and limitations into the practice of design, operations, and safety. The HFG serves as a complement to other primary design references and standards. It does not duplicate or replace them. It is an additional tool for the engineer to use in designing and operating roadways that are safely usable by the broad range of road users.

1.2 Overview of the HFG

This document provides practitioners who design and operate streets and highways with relevant human factors data and principles, in a useful guideline form. The ITE *Traffic Engineering Handbook* (Pline, 1999) cites a definition of "traffic engineering" as "that branch of engineering which applies technology, science, and human factors to the planning, design, operations and management of roads, streets, bikeways, highways, their networks, terminals, and abutting lands." Thus the discipline of human factors is recognized as an integral contributor to traffic engineering practice. Many highway designers and traffic engineers, however, do not have a clear understanding of what human factors is and how its principles are relevant to their work.

Human factors is an applied, scientific discipline that tries to enhance the relationship between devices and systems, and the people who are meant to use them. As a discipline, human factors approaches system design with the "user" as its focal point. Human factors practitioners bring expert knowledge concerning the capabilities and limitations of human beings that are important for the design of devices and systems of many kinds. There has been a number of elements within the field of transportation engineering that have benefited from human factors research, including sight distance requirements; work zone layouts; sign design, placement, and spacing criteria; dimensions for road markings; color specifications; sign letter fonts and icons; and signal timing.

Basic crash statistics in the United States highlight the importance of human factors to road system design. In 2001, for example, there were more than 6 million police-reported (and many more non-reported) collisions in the United States, with attendant loss of life, property, and productivity (NHTSA, 2002). Furthermore, some form of driver error was usually a contributing factor in nearly half (approximately 44%) of the crashes leading to a fatality. "Error" means the road user did not perform his or her task optimally. Misperceptions, slow reactions, and poor decisions are the products of a poor match between the needs and capabilities of drivers and the task demands that they face on the roadway. A more driver-centered approach to highway design and operation will promote continued improvements in highway safety.

While many roadway design practices are based on extensive, well-documented, and fully appropriate behavioral data, this is not always the case. Some design practices recommended by existing standards and guidance can include the following limitations:

- They do not have any empirical basis and/or have not been formally evaluated for adequacy for road users.
- They are based on outdated data that may no longer be representative of current driver behaviors.
- They are based on overly simple models of what road users see or do.
- They are based on incorrect assumptions about road users' capabilities and limitations.
- They do not reflect recent changes in communications technology, vehicle features, roadway features, roadside environment, traffic control devices, or traffic operational characteristics.
- They do not reflect the special needs of some road users, such as older drivers, visually impaired pedestrians, pedestrians with mobility limitations, heavy truck operators, and users of lower-speed alternative transportation devices.
- They do not adequately address trade-offs between conflicting demands that are related to important road user characteristics.
- They may not address specific combinations of roadway design features that can have an impact on road user behavior and subsequent safety.

The HFG provides guidance based on empirical data and expert judgment without the above limitations.

CHAPTER 2

How to Use This Document

2.1 Organization of the HFG

This document is divided into four parts. Part I, Introduction, is a short introduction to the document. The first chapter explains why having human factors guidance is useful. This second chapter explains how to use the document and take advantage of its features.

Part II, Bringing Road User Capabilities into Highway Design and Traffic Engineering Practice, describes a human factors approach to roadway design, presents basic principles and methods, and provides key information about basic road user capabilities. Part II is about road users and how to take their needs into account. It is the basis from which the guidance in Parts III and IV is derived.

Parts III and IV present the actual guidance statements within this document. Part III, Human Factors Guidance for Roadway Location Elements, is organized around specific roadway location elements, such as signalized intersections and work zones. Part IV, Human Factors Guidance for Traffic Engineering Elements, deals with traffic engineering elements such as fixed signage, variable message signs, markings, and lighting. The guidance among many of these chapters is interrelated and the chapter sections link to one another.

2.2 Scope and Limitations of the HFG

The HFG is intended to serve a number of important purposes. Specifically, the HFG provides the following:

- An introduction to the field of human factors as it is applied to highway design and traffic engineering
- Guidance for more optimal design of highways and traffic control devices
- Information linking human factors data and analysis with related guidance in other key highway design and traffic engineering reference documents
- Help in solving problems related to road user considerations, including identifying probable human factors causes or countermeasures
- Objective, defensible information that can be used to support and justify design decisions

In addition, the HFG has some limitations. Specifically, the HFG is *not* the following:

- An alternative to primary design references in highway design and traffic engineering. It is intended to complement and amplify aspects of these other references, such as the MUTCD (FHWA, 2003), *A Policy on Geometric Design of Highways and Streets* (AASHTO, 2004), the *Traffic Control Devices Handbook* (Pline, 2001), the under-development *Highway Safety Manual,* and other guidance.

- A source for comprehensive design specifications nor a redundant treatment of other documents. The HFG is meant to add to, and refine, existing guidance.
- A textbook or tutorial on human factors or a comprehensive source of human factors literature.
- A guide to crash investigation or a comprehensive reference for safety diagnosis.

2.3 The Two-Page Format

In the HFG, a consistent two-page format is used to present the individual human factors guidelines provided in Chapters 5 through 21. On each page, the main issue being addressed by the guideline (e.g., When and How to Use Sight Distance Information, How to Diagnose Sight Distance Problems, etc.) is indicated by centered, bold type within the header. As described in more detail below, the left-hand page presents the title of the guideline; an introduction and overview of the guideline; the guideline itself; the rating associated with the guideline; and a graphic, table, or figure that augments the text information. The right-hand page provides the more detailed supporting rationale for the guideline that a highway designer or traffic engineer may need in order to perform his or her day-to-day design tasks, as well as special design considerations, cross-references to related guidelines, and a list of key references. A sample guideline, with key features highlighted, is shown in Figure 2-1; a detailed description of the presentation format of the guidelines follows.

2.3.1 The Left-Hand Page

The guideline title is indicated by centered, bold type at the top of the left-hand page.

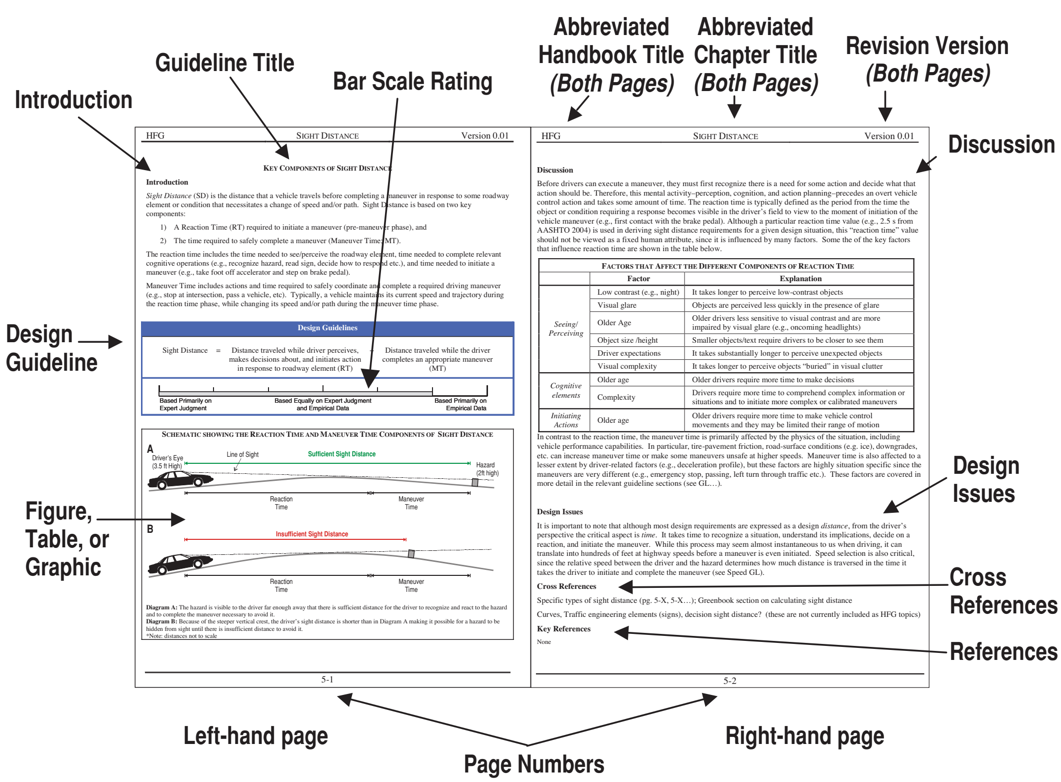


Figure 2-1. Guideline format used in the HFG.

2.3.1.1 Introduction

This subsection briefly defines the guideline and provides basic information about the roadway design parameter and the guideline. For example, this subsection might be used to provide the unit of measurement (e.g., visual angle, meters, foot-lamberts) for the guideline or to provide equations for the derivation of certain parameters.

2.3.1.2 Design Guideline

This subsection presents a quantitative guideline (when possible), either as a point value, a range, or an explicit recommendation. The guideline is always presented prominently and is enclosed in a blue box that is centered on the page.

In some cases, the guideline is presented qualitatively in general terms (e.g., "If the operating speed of a roadway is substantially higher than the design speed, then it may be appropriate to increase sight distance for higher traveling speeds."). However, in most cases, the design guideline is presented quantitatively (e.g., "The reaction time component of stopping sight distance can be expected to be **1.6 s** under good-visibility, good-traction conditions.").

2.3.1.3 The Bar-Scale Rating System

For some design topics, enough empirical data exist to provide well-supported guidelines, and the use of expert judgment is minimal. For others, empirical data have provided only the foundation for a decision about what the guideline should be, but experience and judgment have been used to determine the final guideline. For yet other topics, little or no empirical data were available, and the guideline was based primarily on expert judgment.

To aid highway designers and traffic engineers in making design trade-offs, individual guidelines have been rated according to the relative contribution that empirical data and expert judgment have each made to the guideline. Specifically, each guideline has been rated along a continuum, with each guideline falling somewhere between "Based Primarily on Expert Judgment" and "Based Primarily on Experimental Data." These terms are defined below.

Based Primarily on Expert Judgment. Little or no empirical data were used to develop this guideline. Expert judgment and design convention were used to develop this guideline.

Based Equally on Expert Judgment and Experimental Data. Equal amounts of expert judgment and experimental data were used to develop this guideline. There may have been a lack of consistency in the research finding, requiring greater amounts of expert judgment. Or, research may have been lacking in this area, requiring the results of research from related content domains to be interpreted for use in this context.

Based Primarily on Experimental Data. The guideline is based on high quality and consistent data sources that apply directly to the guideline. Empirical data from highly relevant content domains (e.g., transportation human factors, driver performance data) were primarily used to develop this guideline. Little expert judgment was required to develop this guideline.

2.3.1.4 Figure, Table, or Graphic

This subsection provides a figure, table, or graphic to augment the guideline. This figure, table, or graphic provides "at-a-glance" information considered to be particularly important to the conceptualization and use of the guideline. It provides a visual representation of the guideline (or some aspect of the guideline) that may be difficult to grasp from the design guideline itself, which is quantitative and text based.

This figure, table, or graphic may take many forms, including a drawing depicting a generic application of a guideline or a particular design issue, a flowchart of measurement procedures for the guideline, a table that summarizes the guideline, or schematic examples of specific design solutions.

2.3.2 The Right-Hand Page

2.3.2.1 Discussion

This subsection briefly summarizes the rationale behind the choice of the guideline. In particular, the discussion explains the logic, premises, assumptions, and train-of-thought associated with development of the guideline. The focus is on a presentation of driver limitations and capabilities deemed relevant to the particular guideline topic. The discussion can take many forms, including a brief review of applicable empirical studies, references to traditional design practice, or an analysis of relevant information.

The discussion is presented primarily to help HFG users understand the guideline and to help them explain or justify the guideline to other members of their respective development teams. Also, because these human factors guidelines are expected to be revised as additional empirical data become available, this subsection will be useful to future developers of the guidelines. In particular, the discussion will enable future guideline developers to determine how new information on road users' capabilities and limitations can (or should) be integrated into the existing guidelines.

For example, the design guideline "Determining Stopping Sight Distance" in Chapter 5 has been developed through consideration of experimental data gathered under a range of visibility (good and poor) and vehicle traction (good and poor) conditions. Thus, this guideline is presented as being the sum of driver reaction time plus vehicle deceleration, under a range of visibility/traction conditions. If new driver performance analyses or data for these conditions are obtained (or if new assumptions are made), future design guideline developers will be able to evaluate the quality and applicability of this new information relative to the discussion in the current design guideline "Determining Stopping Sight Distance" and determine what (if any) changes should be made to the design guideline.

2.3.2.2 Design Issues

This subsection presents special design considerations associated with a particular guideline. These special considerations may include design goals from the perspective of other disciplines (e.g., highway engineering, urban planning, physiology), interactions with other guidelines, special difficulties associated with the guideline's conceptualization or measurement, or special performance implications associated with the guideline.

2.3.2.3 Cross References

This subsection lists the titles and page numbers of other guidelines within the handbook that are relevant to the current guideline.

2.3.2.4 References

This subsection lists the references associated with the formulation of the guideline. Each of these references will have been assigned a reference number that was used to note it within the text of the design guideline (e.g., as part of the introduction, discussion, or design issues sections). A complete reference section is provided in Chapter 23 of this document.

2.4 Tutorials

Tutorials are provided in the HFG for important topics, special issues, and detailed procedures that cannot be addressed within the two-page constraints of individual guidelines. Tutorials are currently provided for "Real-World Driver Behavior Versus Design Models" and "Diagnosing Sight Distance Problems and Other Design Deficiencies."

2.5 Other Features

A Glossary is provided in Chapter 24. Technical words and phrases are defined in the Glossary and listed in the Index (Chapter 25). Abbreviations are provided in Chapter 26. Also, equations are numbered sequentially and listed separately in Chapter 27.

(Chapters 24, 25, and 27 will be included in future versions of the HFG.)

PART II

Bringing Road User Capabilities into Highway Design and Traffic Engineering Practice

CHAPTER 3

Finding Information Like a Road User

3.1 Introduction

Some people have said the primary decision-maker in the highway transportation system is the road user. But this statement is just not true. It is not true because many primary decisions are made before the road user ever sees and uses the road. During design and/or reconstruction, primary decisions include the magnitude of the vertical and horizontal alignment, the type of traffic control, and the vehicles permitted on the facility, among others; these decisions are made by highway designers and traffic engineers.

The purpose of this chapter is to remind users of the HFG that road users must read and comprehend from the roadway what the highway designer and traffic engineer intend for them to do. Unfortunately, the road users are not highway designers or traffic engineers and what they comprehend, while totally logical to them, may not be what the highway designers and traffic engineers intended. In short, this chapter illustrates that highway designers and traffic engineers must work together and serve as virtual road users if their goal is to maximize or improve highway safety. This chapter will show through examples why the highway designers and traffic engineers must jointly consider how their individual work may be interpreted by the road user and whether that interpretation promotes user safety.

3.2 Road User as a Component of the Highway System

Highway systems have three major components: the road, traffic control, and users with or without a vehicle (Figure 3-1). For the highway system to operate efficiently and safely, each of these components must work together as a combined unit. This task is not easy, largely because of the wide range of roadway environments, vehicles, and users. Highway systems are composed of local roads, collectors, arterials, and freeways—each having specific design features suitable for their environment. Vehicles using the roads vary widely with respect to weight, size, and performance. Vehicles using the roads may be small, light-weight vehicles with limited power; moderate-size and -powered vehicles; or large, heavy trucks with the horsepower to permit high speeds. Also, the population of road users includes car and truck operators, pedestrians, motorcycle operators, and bicycle riders, all, sometimes, with some degree of physiological disability.

If the goal is to provide highway travel for road users that is both safe and operationally efficient, the needs and constraints of highway design, traffic control, and users must be successfully integrated. Together they must perform as one—not a group of three. Highway designers must know the impact of their design decisions and how they will affect the control needs of traffic engineers as well as the resulting impact they will have on users in performing efficiently and

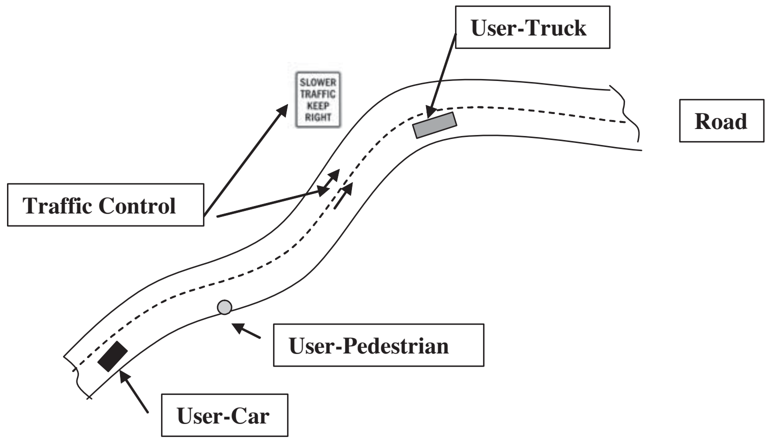


Figure 3-1. Example components of the highway system.

safely. Traffic engineers cannot be expected to solve design problems with traffic engineering fixes. Safe roads are those that are self-explaining where users know how to behave solely because of the design and control of the road (Theeuwes & Godthelp, 1992).

Road users cannot be expected to solve either highway design or traffic engineering problems without making mistakes and/or compromising operational efficiency and safety. Highway system failure in the United States can be measured by the 42,000 fatalities, 3 million injuries, 6 million police-reported crashes, and many more unreported crashes that occur annually (NHTSA, 2004). System failures can be attributed to errors by drivers, design, traffic control, and combinations of these factors (Hauer, 1999).

Design and operation solutions must be jointly developed by highway designers and traffic engineers with both totally aware and cognizant of the needs and limitations of all road users. In effect, they must incorporate into their joint solutions human factor principles that are in keeping with the needs of all users.

3.3 Example Problems of Highway Designers and Traffic Engineers

The following examples illustrate typical design and operational problems where consideration of good human factor principles is appropriate.

- An intersection with the crossing road at an acute angle (30°) has experienced an unusually high number of crashes. See Figures 3-2 and 3-3. The county supervisors have asked the local highway agency for a review and recommendation on what should be done to correct the problem. After reviewing the site, the current and projected traffic flow, and the expected land development in the area, the agency recommended the intersection be changed. Options considered included using stop control on each approach, signalization, and redesign. Neither all-way stop control nor signalization met the MUTCD warrants; therefore, they were discarded as options (FHWA, 2003). Research literature indicates that drivers have difficulty estimating gap size and speed of approaching vehicles at intersections where intersecting roads are not within about 25° of normal (Pline, 1992). The recommended solution was to redesign the crossing road approach to eliminate the acute angle so the approach would be nearly perpendicular to the major road.

Figure 3-2. Northbound approach to example intersection.

- Each end of a 1-mi section of two-lane road in a suburban area had been improved to a four-lane divided highway. The remaining two-lane road had very bad vertical curvature and a cross section with very narrow shoulders; thus the two-lane road environment was very different from either the upstream or downstream road sections. The speed limit was 40 mi/h within the two-lane section and the newer four-lane sections. The two-lane section seemed to have a higher than normal number of crashes. The highway agency requested that the safety, design, and traffic engineers review the roadway and provide recommendations on what should be done. The crash occurrence during the day was found to be not unusually high. At night, however, this was not the case. Drivers approaching the sharp, vertical crests were running off of the road and hitting roadside objects. The engineers recommended that advance curve warning signs, vertical delineators, and roadway lighting be installed in the two-lane section to help prevent drivers approaching crests at night from being overcome by sudden glare produced by opposing vehicles previously hidden in the sags as shown in Figure 3-4.

Figure 3-3. Westbound approach to example intersection.

Figure 3-4. Day and night views of approaching crest.

Some human factor characteristics regarding roadway users are available to help implement preferred design and control solutions. The following are some of those found in the research literature:

- Drivers experience difficulty at intersections in estimating gap size and speed of approaching vehicles (Staplin, Lococo, & Byington, 1998).
- Drivers experience problems in detecting a sharper curve after negotiating several longer radius curves (Glennon, 1996).
- Additional distance and time are required to slow or stop under adverse weather conditions (Baerwald, 1965).
- Excessive messages on changeable message signs (CMSs) can inhibit correct decisions and traffic flow, and safety (Staplin et al., 1998).
- Bright light sources, whether from vehicles or roadside property, can cause glare, user-blinding, and possible loss of vehicle control (Ogden, 1996).
- User decision making takes time but users can only react to about 1 to 1.5 information tasks or actions per second (AASHTO, 2004).

While the previous items and two examples are not an exhaustive list, they illustrate a few of the many user problems encountered. Highway designers and traffic engineers must be aware of such human factor characteristics and use them in a way that will improve or optimize the safety of the road system they are designing and controlling.

3.4 How Road Users Seek Information

Theeuwes and Godthelp (1992) have described self-explaining roads as road environments where users know how to behave based on the road design. Unfortunately, many roads today are not self-explaining. Self-explaining roads induce user behavior based on the design and not on “external agents” like signs and traffic signals. When the road is not self-explaining, highway operations can be inefficient, delayed, and unsafe, plus user speeds are more varied. Road users continuously seek information under many different conditions—from when the road environment has few vehicles or other users present to when many vehicles and other users are present; however, road users’ access to information may be more difficult under conditions of darkness, inclement weather, glare from sunlight, etc. According to research findings, users categorize roads during their driving task and formulate their temporal reactions based on previously learned behavior (Theeuwes & Diks, 1995). Design standards by functional classification enhance user-learned behavior and their system expectations.

Road users seek information for navigation, guidance, and control (Alexander & Lunenfeld, 1990). Navigation information relates to getting from point A to B; guidance information relates to lane selection; and control relates to selection of vehicle speed, level of braking, and steering. The information road users seek varies according to the situation—sometimes complex and sometimes simple.

How road users seek information is fairly simple. They scan the road environment seeking the most meaningful information (MMI) needed for that particular road location and point in time. How they scan the environment depends on the presence or absence of potentially hazardous situations as they perceive them. Road users are generally alert for both longitudinal and lateral hazards (i.e., other vehicles, pedestrians, animals, or objects near their planned path); they develop an expectancy of the roadway based on what they previously experienced upstream. They seek the information they need by searching the road environment in front of, behind, and to the sides of the vehicle they are driving. This searching and scanning process is continuous for the duration of the trip.

Scanning of the road environment is a time-based activity. The speed at which scanning is performed is not constant but it is a function of the road environment (i.e., geometric design, vehicle speed, cross section elements, traffic volume, weather, vehicle mix, presence of pedestrians, driver experience, traffic control, etc). If the environment has no threatening activity perceived by the road user, the scanning rate may be slower, and he or she may have time for scenic pleasures. At other times the visual scanning rate may be greater because of enhanced road environment activity. Early notable research on driving scanning was conducted by Mourant, Rockwell, and Rackoff (1969).

Road users can receive and process only a finite amount of information in a short time period, not an infinite set of information. To describe perception-reaction time (PRT), Johannson and Rumar (1971) use a scale ranging from 0 to 6 bits of unexpected and expected information that a road user can process per second. They found the average driver processes about 1 and 1.5 bits of information per second for unexpected and expected situations, respectively. The more difficult or competing tasks a road user is confronted with, the longer he/she will take to select the response to initiate; also, not all road users perform the same (Johannson & Rumar, 1971). According to AASHTO, for unexpected situations some drivers take as long as 2.7 seconds (AASHTO, 2004). Therefore, highway designers and traffic engineers must plan and develop the road environment temporally and in accordance with the scanning ability of the road users.

Highway designers and traffic engineers often use distance-speed criteria (i.e., stopping distance, passing distance, intersection sight distance) to specify road design elements and placement of traffic control devices, but distance criteria are always based on time and how road users use it.

3.5 Examples of User-Scanned Road Environments

The purpose of this section is to illustrate the features that road users would classify as the MMI for making their next driving decision using a photograph of an example location. This kind of research is useful to highway designers and traffic engineers because it identifies what information road users are using and whether the individual bits of information are useful, competing, or potentially misleading to road users' decision making and safety.

The following examples were prepared by showing subjects hard copies of the roadway scenes, some with approaching vehicles and some with no approaching vehicles (Tignor, 2006). The subjects were asked to identify the most important information they would consider should they confront that situation when driving. A color code was used to prioritize the information from most to least important. The priority of the color code was from left to right with dark green as priority one. The road is in a suburban environment and it has a speed limit of 35 mi/h.

3.5.1 Example 1, View 1

The first example illustrates what subjects identify as MMI when there is a lot of activity in the road environment. As shown in Figure 3-5, when no vehicles are moving toward the road users (middle photograph), many items are identified as possible sources of meaningful information even though the road environment has many parked vehicles, three intersections, and a distant curve.

The presence of approaching vehicles (bottom photograph) changes what road users consider as important information. Approaching vehicles clearly induce the road users to concentrate their attention to them as sources of MMI. The items having the highest frequency of visual sources of meaningful information are approaching vehicles, the nearest intersections, and a distant curve.

3.5.2 Example 2, View 4

The second example illustrates how road users are adversely affected when roadway design and traffic control features are not appropriately coordinated. Figure 3-6 shows drivers approaching a very short vertical curve (top photograph) that has the potential of hiding downstream vehicles just beyond the crest of the curve. Just upstream of the crest is a speed limit sign.

The colored circles in the figure (middle and bottom photographs) show that many of the subjects look to the speed limit sign as the first or second most meaningful source of information as opposed to the crest beyond, which could hide a vehicle or other hazard in the roadway. They look at the speed limit sign whether a vehicle is or is not ahead of them. The short vertical curve is a roadway hazard, but the speed limit sign creates an additional hazard. If the road design and traffic engineering had been coordinated, more time would have been available for the road user to seek the MMI for assessing a potential conflict at the crest. From a safety perspective the speed limit sign should be relocated.

3.5.3 Observations from Examples

The previous two examples show some interesting results:

1. The selection process is different depending upon the presence or absence of other vehicles. When the roadway has no other vehicles in the forward view, the subjects' search is longitudinally and laterally broad and downstream from their current road location. They are primarily seeking information for guiding and controlling the vehicle.
2. When other vehicles are within their forward view, whether approaching or traveling in the same direction, the subjects' search is more selective. They tend to focus first on other vehicles in the road environment and second on information for guidance and control.
3. The examples illustrate how important it is for the road design and traffic control components to be coordinated to prevent competition for road user attention, which compromises user safety.

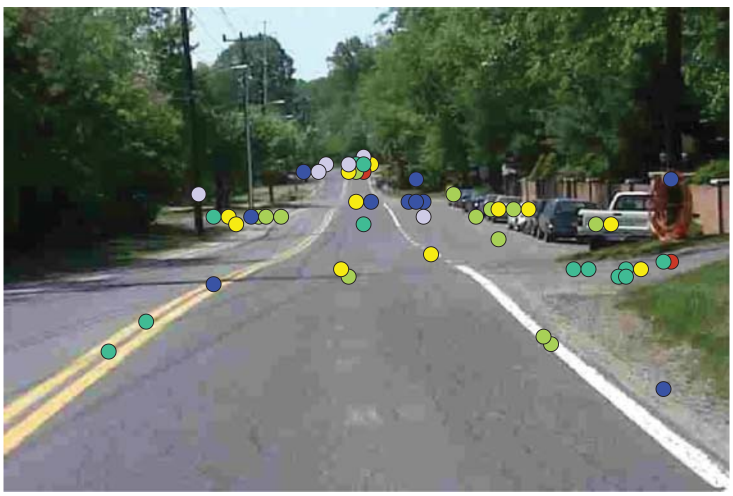
3.6 How Highway Designers and Traffic Engineers Work Together for Road Users

3.6.1 Serve as Virtual Road Users

Highway designers and traffic engineers must serve as virtual road users. They must view the route in small, incremental steps as if they were road users traveling downstream and gathering

1- Near Gordon Street

1 - Near Gordon Street



1t - Near Gordon Street

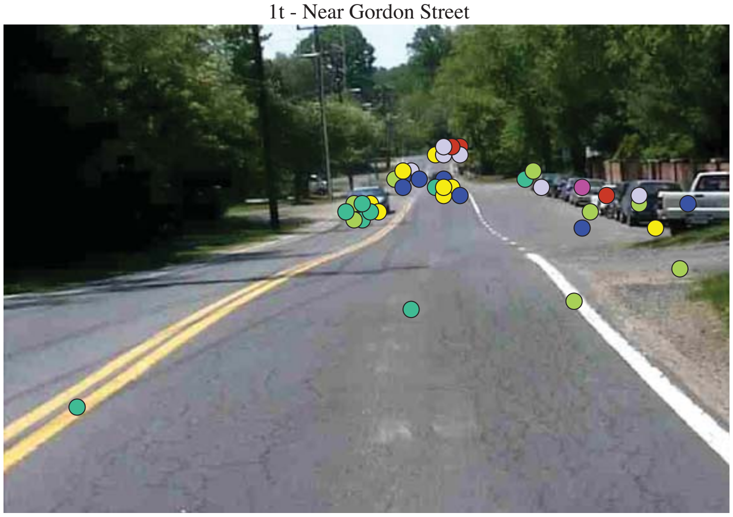


Figure 3-5. Example 1, View 1.

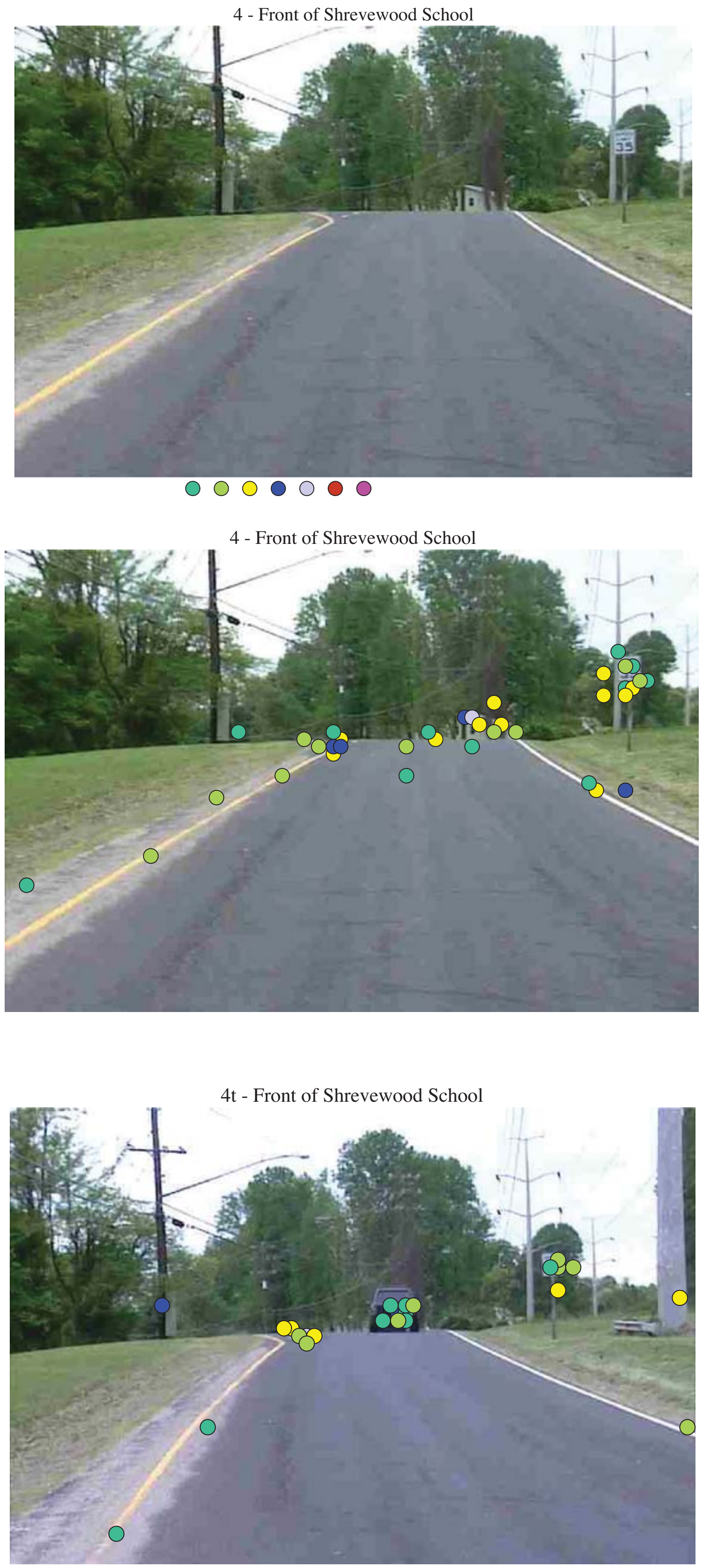


Figure 3-6. Example 2, View 4.

information in small time and space increments; they must learn from road users' experiences. Identifying what road users consider important is not easy.

Ninety percent of drivers' tasks are obtaining visual information from the roadway to maneuver their vehicle safely (Hartman, 1970). This visual information cannot be confusing and it must be complete and accurate if safe decisions are to be made. Road safety audits and a procedure used by McGee called SLIDE (Simplified Location of Information Deficiencies) depend on professional staff to identify safety problems associated with on-road design and traffic control applications and omissions (Morgan, 1999; McGee, Hughes, & Hostetter, 1986). The MMI procedure obtains information directly from road users about what in the road environment they consider important to their driving decisions. User input is important because 27% of road crashes are attributed to a joint association of road user and roadway environmental problems (Schlegel, 1993).

Eye scanning technology, in both real and simulated conditions, has also been used for obtaining information on what drivers view in the visual field. Although vast and time consuming to decipher, eye scanning data are interesting. The literature reports on search patterns of novice and experienced drivers (Mourant & Rockwell, 1972), the degrees of longitudinal and lateral eye fixation zones (Shinar, McDowell, & Rockwell, 1977), design of controls on vehicle instrument panels (Dingus, Antin, Hulse, & Wierwille, 1989), and signing (Smiley et al., 2005). For example, Mourant and Rockwell (1972) estimated 70% of driver eye pursuits were for lateral position. Shinar et al. (1977) found lateral eye movements increase during curve negotiation on two-lane roads and they begin 2 to 3 s before entering a curve. On right turns, drivers spend 55% of the time looking at the road and only 5% looking to the left. Similarly on left turns, drivers spend 38% of the time looking at the road and 24% of the time looking to the right. Recarte and Nunes (2000) found mean horizontal visual fixation to be $\pm 0.5°$ from center with a $\pm 2°$ standard deviation and mean vertical visual fixation to be 1° below the horizon with a $\pm 1°$ standard deviation. Harbluk, Noy and Eizenman (2002) reported 80% of all driver fixations are within the central 15° of the visual field. Gordon (1966) reported that 98% of driver fixations fell on or near the road edge or centerline. He also reported drivers look about 6.5 ft from the right edge of the road when following a left curve, and about 9 ft from the right edge of the road when turning right. While these findings are interesting, the research analysts must infer or guess what items are really important to road users' driving decisions. Consequently, the results from eye scanning research have not been previously incorporated into design standards and guidelines.

Yet, highway designers and traffic engineers must identify jointly the important design and traffic control elements that are critical to road user decision making. They must identify potentially conflicting and misleading information whether it be geometric, traffic control, or the combination of both. The roadway environment created must provide continuous, clear information that the road user can interpret quickly, accurately, and safely.

3.6.2 Incorporate Substantive Safety and Self-Explaining Designs

A substantive safe road system must be created (Hauer, 1999). When a road system is properly created, potential errors will be prevented by elimination of the following:

- The unintended use of infrastructure
- Non-uniformity and inconsistency of design and traffic control applications
- Encounters with large differences in speed
- Uncertain driver behavior

Self-explaining designs create road categories that are recognizable by users and are appropriate for the following:

- Flow requirements (i.e., small to large volumes)
- Speed functions (i.e., slow to high speed)
- Access functions (i.e., local roads, collectors, arterials)

Lastly, self-explaining roads have the following characteristics:

- Road environments where road users know how to behave simply by the design
- Road types in keeping with road user expectations based on visual information obtained and object conspicuity
- A driving environment that is intuitive and transparent (Theeuwes & Godthelp, 1992)

3.6.3 Jointly Develop Road Systems

To achieve an acceptable level of system safety, highway designers and traffic engineers need to serve as virtual road users. They must place themselves in the shoes of the road user and consider what the road user will identify as most important both during day and night conditions. To identify the MMI, the highway designer and traffic engineer will together need to apply principles similar to those found in road safety audits (Morgan, 1999):

- Highway designers and traffic engineers must jointly develop and agree on the goals for the road system that will meet the objectives of the road agency but have the safety of users in the forefront.
- Highway designers and traffic engineers must jointly develop, review, and approve the design and operational plans for each project. The designs will be self-explaining to the road users and provide substantive safety for them.
- Whether projects are new construction, upgrades, or maintenance, highway designers and traffic engineers must jointly oversee the field work and make inspections as virtual road users before the start of new operations. If misleading individual or combined design and control features are found, they should be eliminated before the road is opened to traffic.

CHAPTER 4

Integrating Road User, Highway Design, and Traffic Engineering Needs

4.1 Introduction

The purpose of this chapter is to help highway designers and traffic engineers function as virtual road users. Not all road user situations are the same; some are more demanding than others. The different situations make the highway designer's and the traffic engineer's work more challenging, more intricate, and more demanding. They must consider the human factor characteristics of the user in conjunction with four major components: (1) the geometric design elements, (2) roadway and vehicle operations, (3) type of highway, and (4) the roadway environment. At any given location, the roadway user only has a finite amount of time to make decisions. Users, even with total visual attention, may not have sufficient time, under demanding real-time conditions, to extract as much information as desired. Sometimes road users must make choices about what information is processed. The scope of this chapter is to illustrate the breadth of the human factor considerations as magnified by the four major components and how highway designers and traffic engineers must integrate them all in safety-oriented solutions given the constraints of the road user. This chapter also shows, through examples, how on-road problems can be reviewed and improved by using the recommendations in Parts III and IV. A problem description, complete with written recommended solutions and video animations ***(to be developed later),*** are included.

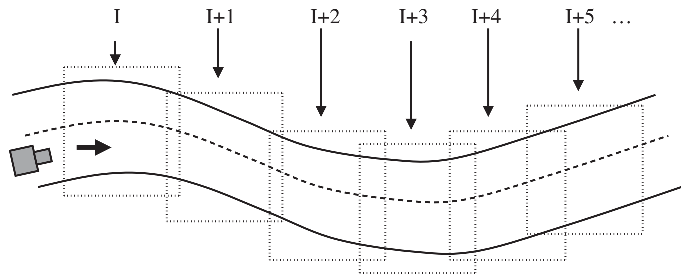
4.2 Iterative Review Steps to Achieve Good Human Factor Applications

4.2.1 Process

Whether driving, walking, running, or bicycle riding, road users continuously scan the downstream environment that they are entering (Robinson, Erickson, Thurston, & Clark, 1972). The scanning can be represented as shown in Figure 4-1.

In the figure, a vehicle is proceeding from left to right. At location or time *I,* the user observes the road environment and corresponding traffic conditions. He or she identifies the MMI at that point in time and space and assesses what guidance and control is needed (Tignor, 2006). The user implements that control and continues with it until scanning location or time *I*+1 when an information refresher is determined necessary. Any number of conditions could initiate the need for an information refresher. The following are typical examples that could induce a need for new information at *I*+1:

- The cross section may have an increase or decrease in the number of lanes.
- Downstream traffic may be slowing or stopping in the lane the user is traveling.



I = User scanning steps (vary in size)

Figure 4-1. Road user scanning steps for finding most meaningful information (MMI).

- A pedestrian may be walking along the shoulder and without looking turn in front of the approaching user.
- Traffic may be entering the road from a side street or business establishment.
- A user is approaching a traffic sign with letters that are too small to read.
- A traffic signal is changing from green to amber.
- The road appears to be curving sharply to the right while the lane width is decreasing.

Each of these examples would necessitate that the road user reassess his or her information and control at *I* and determine if control modification is required. The challenge for virtual users (i.e., highway designers and traffic engineers) is to determine what kind of infrastructure modification is required, if any, from locations *I, I*+1, . . . *I*+*n.*

The scanning step sizes may vary and are influenced by the road user, type of operation, highway character, and environment. Some of these variables are listed in Table 4-1.

All road users are continuously sampling the road environment for information. The sampling rate can be represented as follows:

$$\text{Sampling Rate} = f\left(\text{user, operations, highway, environment}\right)$$

Table 4-1. Scanning step variables.

Factor	Variable	
User	Age Vision Experience	Cognitive ability Road familiarity
Operations	Speed Vehicle type Traffic volume	One-way flow Two-way flow Control type
Highway	Functional class Lane width Shoulder width Sight distance Pavement type and condition	Condition Roadside Grades Curvature
Environment	Weather Land use Pedestrians Urban	Rural Time of day Light condition Scenic/interest attractions

Through road scanning the user is updating his or her information database for making decisions. This process can be expressed as follows:

$$\text{Information}(t) = \text{Information}(t-1) + \text{changes during } \Delta t$$

Where

t = time
Δt = sampling interval

The real challenge then is to identify the changes that have occurred during the sampling interval (Δt). Changes include those elements detected by the road user within the visual scans or *I* steps. They may be previously seen items or new items not seen previously. The importance of the items may be elevated or reduced depending on their relationship to the user's need at the time (t). They may have a direct impact on the user's task of maintaining control of the vehicle or they may only serve as information useful for defining the approaching highway, operating, and environmental conditions.

4.2.2 Size of Iterative Steps

The highway designer and the traffic engineer must examine the road environment in incremental steps similar to those steps described in the previous section to ensure the road user will not be overloaded with temporal tasks and decisions. In short, good human factor principles must be integrated into the design of the road system.

The sizes of the iterative steps are not going to be the same for all road environments. They will vary depending on the road user, the type of highway, the operations, and the environment. The iterative steps, however, must overlap from one section to the next to ensure continuity of the travel path and that no potentially meaningful information for road users will be overlooked. The highway designers and traffic engineers must jointly examine the road environment—i.e., lane alignment (roadway and intersections), signing (advisory, regulatory and guidance), and operations (normal and work zones)—relative to the likelihood users will be able to perform the required tasks safely and efficiently within the time and space available.

Table 4-2 is a breakdown of some of the different steps taken by road users and their respective time restraints.

4.2.3 Identification of Potentially Conflicting or Missing Information

Identification of potentially conflicting, confusing, or missing information is probably one of the most important tasks of designers and traffic engineers. As virtual road users, designers and traffic engineers must examine the roadway environment for information conflicts that may mislead or confuse road users. They must anticipate what information the road user requires and where it is needed so appropriate design elements or traffic control can be integrated into the design and operational plans. Missing information is not helpful to the road user. In short, designers and traffic engineers must also seek road environments that are self-explaining, quickly understood, and easy for users to act upon (Theeuwes & Godthelp, 1992).

The example and analysis detailed in the next section illustrates problems that can be created by not properly relating the roadway geometrics to the traffic control. Together, designers and traffic engineers need to identify these problems when serving as virtual road users.

Table 4-2. Iterative steps used in sampling the road environment for information.

Step	Timing
Eye fixation time	• 0.20 to 0.25 s (Homburger & Kell, 1988) • 0.25 to 0.33 s (Mourant et al., 1969)
Turn head to the left	• 1.31 to 1.52 s (Mourant & Donohue, 1974)
Turn head to the right	• 1.09 to 1.14 s (Mourant & Donohue, 1974)
Car following	• Attention to lead vehicle reduces attention elsewhere by 15% (Mourant et al., 1969)
Sign detection	• Look time: 0.5 s (Zwahlen, 1995; Zwahlen & Schnell, 1998) • Saccade time: 0.03 s (Zwahlen, 1995; Zwahlen & Schnell, 1998) • Time for fixation on sign: 0.3 to 0.8 s (Zwahlen, 1995; Zwahlen & Schnell, 1998)
Sign reading	*Variable message signs* (Staplin et al., 1998) • Minimum exposure time:1 s/short word (four to eight characters) or 2 s/unit of information, whichever is larger • Reading time: 1 to 1.5 s/unit of information in light traffic • Minimum phase or page time: 3 s/page for a three-line message *Video signs* (Smiley et al., 2005) • 20% of glances to video signs exceeded 0.75 s • 38% of glances occurred when headways were less than 1 s • 25% of the glances were at angles greater than 20° • 76% of drivers looked ahead, 7% at signs and signals, 6% at pedestrians • Glances at video signs occurred with longer headways than with static signs
Use of mirrors	• 0.87 s, rear view (Mourant & Rockwell, 1972) • 0.98 s, left side (Mourant & Rockwell, 1972) • 0.78 s, rear view (Mourant & Donohue, 1974) • 0.88 s, left side (Mourant & Donohue, 1974)

4.3 Use of Parts III and IV for Specifying Designs

Parts III and IV are where explicit guidance statements are found. Before using the HFG for developing a solution to a problem, the HFG user must first study and understand the issues involved. For example, the illustrative example in section 4.3.1 involves both geometric design and signing issues. The approaching road users see a fork in the road and seven sets of signs communicating information to drivers. Because the signs are spaced too close together and the road is making an abrupt turn to the left, approaching drivers have insufficient time to scan the environment and make decisions on navigation, guidance, and control. Part III, Chapter 6, Curves, and Part IV, Chapter 18, Signing, are the sections of the HFG that will be used for developing the solution to this problem.

4.3.1 Detailed Description of Illustrative Example

A two-lane arterial roadway (US 293) crosses over a parkway (Route 6) that prohibits trucks. The arterial approaches the parkway from a tangent, but it then crosses over the parkway by curving sharply to the left. The connection to the parkway is a ramp that appears as a continuation of the arterial tangent. Because trucks are prevented from using the parkway, a sign directs them to an alternative roadway to reach the portion of Route 6 with unrestricted access. See Figure 4-2.

Figure 4-2. Improper signing and geometrics.

Various problems are found at this location:

- The alignment of the arterial and parkway ramp is not self-explaining. The first route marker shows Route 6 going to the right. The first word sign, on glance, suggests Route 6 is going to the left. The first line on the first word sign indicates the sign is for trucks and trailers, but that is not immediately clear to unfamiliar, approaching drivers. Car drivers also visually key on the sign. Confusion is created as to which road is Route 6, Route 293, and Route 9W.

- Because of the location of the signs and their close spacing, drivers have insufficient time to identify the important information. Also, the word signs have too many lines of information for users to read and interpret.
- The heights of the letters on the signs are too small.
- The message as to where trucks are permitted is not sufficiently clear.
- As seen by the skid marks near the gore in Figure 4-2 (bottom photograph), road users have difficulty in deciding whether to follow the road to the left or continue straight onto the ramp to the parkway.
- Access to intersecting routes or ramps should not appear to be a continuation of the approaching, main road.

Parts III and IV will be used together to develop a joint candidate design and control solution having a high level of road user acceptance, understanding, and safety. Candidate solutions must be in compliance with AASHTO design and MUTCD control standards (AASHTO, 2004; FHWA, 2003).

An example will be added at a later time.

4.4 Video and Animation Illustrations

It is intended that in future versions of the HFG, the original problem can be illustrated with a video of a vehicle approaching the interchange. The video will then be altered to show what the interchange will look like with improved signing.

As an alternative (or addition) to video, an animation of the problem will be developed showing possible improvements using (a) only geometric changes, (b) only signing changes, (c) both geometric and signing changes.

PART III

Human Factors Guidance for Roadway Location Elements

CHAPTER 5

Sight Distance Guidelines

KEY COMPONENTS OF SIGHT DISTANCE

Introduction

Sight distance (SD) is the distance that a vehicle travels before completing a maneuver in response to some roadway element, hazard, or condition that necessitates a change of speed and/or path. Sight distance is based on two key components:

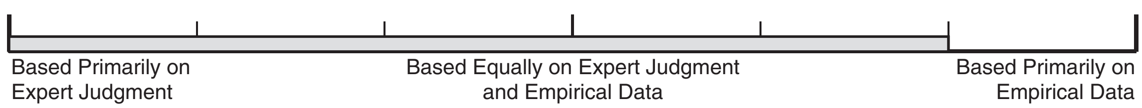
- The perception-reaction time (PRT) required to initiate a maneuver (pre-maneuver phase)
- The time required to safely complete a maneuver (MT).

The PRT component includes the time needed to see/perceive the roadway element, time needed to complete relevant cognitive operations (e.g., recognize hazard, read sign, decide how to respond, etc.), and time needed to initiate a maneuver (e.g., take foot off accelerator and step on brake pedal).

MT includes actions and time required to safely coordinate and complete a required driving maneuver (e.g., stop at intersection, pass a vehicle, etc.). Typically, a vehicle maintains its current speed and trajectory during the PRT phase, while changing its speed and/or path during the MT phase.

Design Guidelines

Sight Distance	=	Distance traveled while driver perceives, makes decisions about, and initiates action in response to roadway element (PRT)	+	Distance traveled while the driver completes an appropriate maneuver (MT)



SCHEMATIC SHOWING THE PERCEPTION-REACTION TIME AND MANEUVER TIME COMPONENTS OF SIGHT DISTANCE

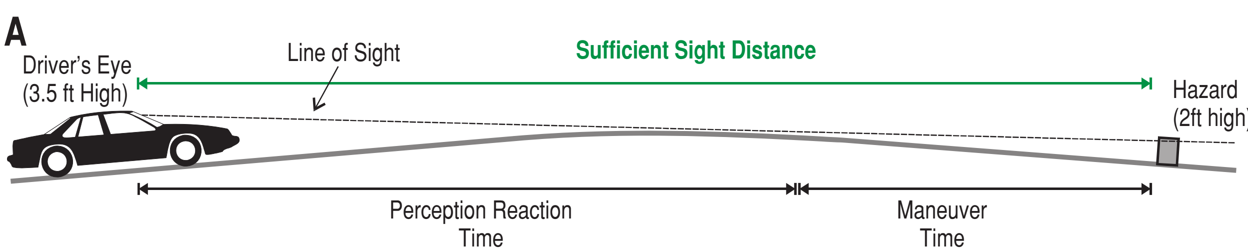


Diagram A: The hazard is visible to the driver far enough away that there is sufficient distance for the driver to recognize and react to the hazard and to complete the maneuver necessary to avoid it.

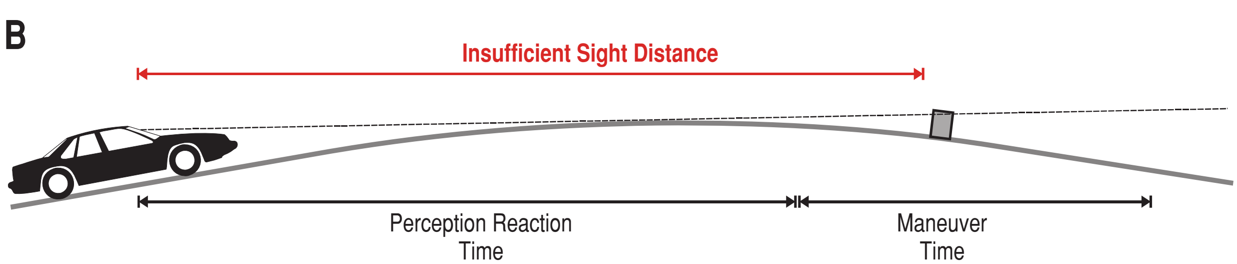


Diagram B: Because of the steeper vertical crest, the driver's sight distance is shorter than in Diagram A making it possible for a hazard to be hidden from sight until there is i*nsufficient distance to avoid it.*
**Note: distances not to scale*

Discussion

Before drivers can execute a maneuver, they must first recognize that some action is required and decide what that action should be. Therefore, this mental activity—perception, cognition, and action planning—precedes an overt vehicle control action and takes some amount of time. The PRT is typically defined as the period from the time the object or condition requiring a response becomes visible in the driver's field of view to the moment of initiation of the vehicle maneuver (e.g., first contact with the brake pedal). Although a particular PRT value (e.g., 2.5 s (*1*)) is used in deriving sight distance requirements for a given design situation, this PRT value should not be viewed as a fixed human attribute, because it is influenced by many factors. Some of the key factors that influence PRT are shown in the table below.

FACTORS THAT AFFECT THE DIFFERENT COMPONENTS OF PERCEPTION-REACTION TIME

Activity	Factor	Explanation
Seeing/ Perceiving	Low contrast (e.g., night)	Drivers take longer to perceive low-contrast objects.
	Visual glare	Objects are perceived less quickly in the presence of glare.
	Older age	Older drivers are less sensitive to visual contrast and are more impaired by visual glare (e.g., oncoming headlights).
	Object size/height	Smaller objects/text require drivers to be closer to see them.
	Driver expectations	Drivers take substantially longer to perceive unexpected objects.
	Visual complexity	Drivers take longer to perceive objects "buried" in visual clutter.
	Driver experience/familiarity	PRT to objects and situations will generally be faster with increased experience and/or familiarity.
Cognitive Elements	Older age	Older drivers require more time to make decisions.
	Complexity	Drivers require more time to comprehend complex information or situations and to initiate more complex or calibrated maneuvers.
Initiating Actions	Older age	Older drivers require more time to make vehicle control movements and their range of motion may be limited.

In contrast to the PRT, the MT is primarily affected by the physics of the situation, including vehicle performance capabilities. In particular, tire-pavement friction, road-surface conditions (e.g., ice), and downgrades can increase MT or make some maneuvers unsafe at higher speeds. MT is also affected to a lesser extent by driver-related factors (e.g., deceleration profile), but these factors are highly situation specific because the maneuvers are very different (e.g., emergency stop, passing, left turn through traffic, etc.).

Design Issues

Although most design requirements are expressed as a design distance, from the driver's perspective, the critical aspect is *time*. Time is required to recognize a situation, understand its implications, decide on a reaction, and initiate the maneuver. While this process may seem almost instantaneous to us when driving, it can translate into hundreds of feet at highway speeds before a maneuver is even initiated. Speed selection is also critical, because the relative speed between the driver and the hazard determines how much distance is traversed in the time required for the driver to initiate and complete the maneuver.

Cross References

Determining Intersection Sight Distance, 5-6
Determining When to Use Decision Sight Distance, 5-8
Determining Passing Sight Distance, 5-10

Key References

1. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington DC.

DETERMINING STOPPING SIGHT DISTANCE

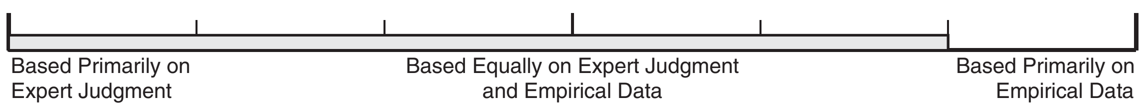
Introduction

Stopping sight distance (SSD) is the distance from a stopping requirement (such as a hazard) that is required for a vehicle traveling at or near design speed to be able to stop before reaching that stopping requirement. Stopping sight distance depends on (1) the time required for a driver to perceive and respond to the stopping requirement (PRT) and (2) how aggressively the driver decelerates (MT).

Design Guidelines

EQUATIONS FOR STOPPING SIGHT DISTANCE DESIGN VALUES

Metric	US Customary
$$SSD = 0.278Vt_{RT} + 0.039\frac{V^2}{a}$$ Where: t_{RT} = perception-reaction time; V = design speed, km/h; a = deceleration level, m/s^2 (see discussion)	$$SSD = 1.47Vt_{RT} + 1.075\frac{V^2}{a}$$ Where: t_{RT} = perception-reaction time; V = design speed, mi/h; a = deceleration level, ft/s^2 (see discussion)



The following table presents driver PRTs and mean deceleration levels under favorable and unfavorable conditions calculated from driver responses to unexpected roadway hazards (*1, 2*). The mean deceleration rates and 85th percentile values (3.7 m/s^2) are higher than those recommended in Lerner, Huey, McGee and Sullivan (*1*), but are shown to provide an indication of driver performance capabilities under emergency conditions.

Visibility	*Good Traction Conditions*			*Poor Traction Condition*		
	PRT	**Mean Deceleration Level (*a*)**		**PRT**	**Mean Deceleration Level (*a*)**	
		Metric	*US Customary*		*Metric*	*US Customary*
Good	1.6 s	5.4 m/s^2	17.7 ft/s^2	1.6 s	4.2 m/s^2	13.8 ft/s^2
Poor	5+ s	5.4 m/s^2	17.7 ft/s^2	5+ s	4.2 m/s^2	13.8 ft/s^2

Although the mean deceleration level differs for good (5.4 m/s^2) and poor (4.2 m/s^2) traction conditions, the 85th percentile values are the same (3.7 m/s^2).

Component	Favorable Conditions	Unfavorable Conditions
PRT	*Daytime* Hazard clearly visible and directly in driver's line of sight *Nighttime* Self-illuminated or retro-reflectorized hazard, with a lighting configuration that is immediately recognizable, near driver's line of sight	*Daytime* Hazard camouflaged by background and initially off line of sight *Nighttime* Hazard unreflectorized and not self-illuminated Lighting configuration is unfamiliar to the driver Low beams with or without street lighting Glare from oncoming vehicles
MT	Tangent with no grade Dry or wet pavement Passenger vehicles; tires in good condition Unexpected object	Curve Downgrade

Discussion

The PRT stage is significantly influenced by visibility conditions. In particular, the distance at which drivers can see an unilluminated, unreflectorized hazard depends on their headlights, their sensitivity to contrast, and their expectation of seeing the hazard. When drivers are not expecting a particular low-contrast hazard, their seeing distance is one half of that which would pertain if the object were expected. A very-low-contrast hazard may not even be detected in time to start braking. At speeds of 60 km/h and greater, using low-beam headlights, most drivers will be too close to an unexpected, unreflectorized hazard at the point they can detect it in time to stop (e.g., pedestrian in a dark coat). Also, the PRT component can be further increased by high workload (e.g., traffic merging, reading signs), fatigue, and impairment.

From an engineering perspective, the deceleration maneuver is significantly influenced by road surface conditions. From a human factors perspective, however, stopping is also influenced by the deceleration level that a driver adopts (which affects the braking efficiency). Under wet conditions, with standard brakes, the mean constant deceleration is about 0.43 *g* (54% of the pavement's coefficient of friction), and the 85th percentile is 0.38 *g* (47%). On wet pavements with anti-locking brake systems (ABSs), the mean constant deceleration is about 0.53 *g* (66% of the pavement's coefficient of friction), and the 85th percentile is about 0.45 *g* (56%). Under unfavorable conditions, slightly lower braking efficiencies (by 2% to 8%) are obtained on curves and tangents, but this information is based on physics because no human factors studies are available. Note also that downgrade MT can be increased by age and gender because older drivers and women will not apply as much braking force as younger drivers and males.

Some research suggests that under most rushed braking situations, drivers stop rapidly, but not to the point of locked wheel braking (in locked wheel braking, which is typical in crashes, drivers are 100% efficient in making use of the available pavement friction) (*2*). The mean maximum deceleration in one comprehensive study was about 75% of the pavement's coefficient of friction (*2*).

Design Issues

Stopping sight distance should always be provided because any road location can become a hazard. One study found that the most common objects hit on sight-restricted curves were large animals and parked cars (e.g., as provided by AASHTO (*3*)), the presence of which can create a hazard on any road section(*2*). If SSD is below standard at a number of locations then priorities must be set. Examples of hazards and conditions that may be high priority with respect to the need for SSD are:

- Change in lane width
- Reduction in lateral clearance
- Beginning of hazardous side slope
- Crest vertical curve
- Horizontal curve
- Driveway
- Narrow bridge
- Roadside hazards (e.g., boulder markers at driveways)
- Unmarked crossovers on high-speed rural arterials
- Unlit pedestrian crosswalks
- High-volume pedestrian crosswalks
- Frequent presence of parked vehicles very near or intruding into through lane

For design purposes, neither rapid nor locked wheel braking is a desirable driver response, because of the risk of skidding, or of a rear-end crash when there is a following vehicle. It should also be noted that the AASHTO model of driver deceleration assumes constant deceleration throughout the braking maneuver; however, empirical data suggest that maximum deceleration is generally not exhibited until the last part of the braking when the vehicle has slowed and come closer to the unexpected object (*2*). Under wet conditions, the 95th percentile value for equivalent constant deceleration without ABSs was 0.29 *g* (equivalent to 2.8 m/s^2 [9.3 ft/s^2]) and with ABSs, 0.41 *g* (equivalent to 4 m/s^2 [13.2 ft/s^2]).

Many design references use the term "design speed" to characterize the expected driving speed on a roadway. However, as noted in "Influence of Speed on Sight Distance" (page 5-12 of this document), neither design speed nor posted speed is always the best determinant of actual driving speed. When available, actual operating speeds should be used instead of design speed to help determine needed sight distance.

Cross References

Key Components of Sight Distance, 5-2
Determining Intersection Sight Distance, 5-6
Determining When to Use Decision Sight Distance, 5-8

Key References

1. Lerner, N., Huey, R.W., McGee, H.W., and Sullivan, A. (1995). *Older Driver Perception-Reaction Time for Intersection Sight Distance and Object Detection. Volume I, Final Report* (FHWA-RD-93-168). Washington, DC: FHWA.
2. Fambro, D.B., Fitzpatrick, K., and Koppa, R.J. (1997). *NCHRP Report 400: Determination of Stopping Sight Distances*. Washington, DC: Transportation Research Board.
3. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.

DETERMINING INTERSECTION SIGHT DISTANCE

Introduction

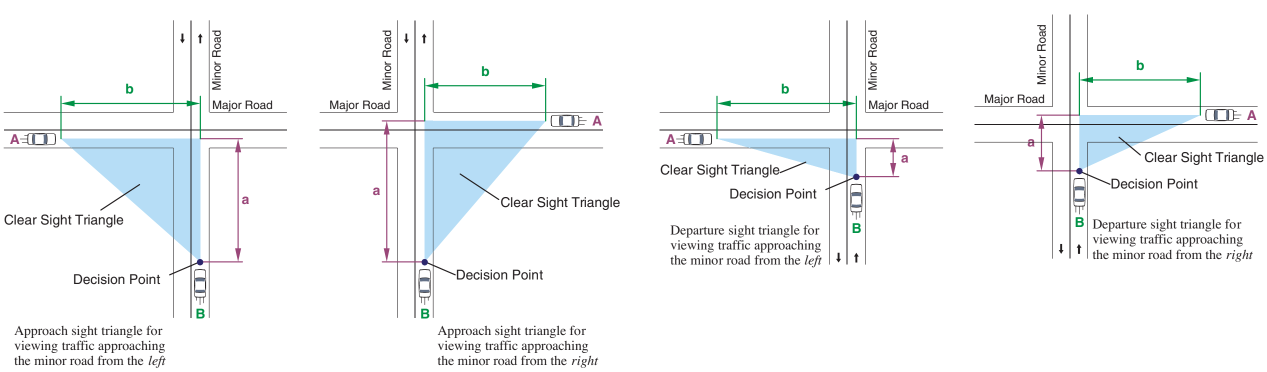
Providing stopping sight distance at intersections is fundamental to intersection operation. In addition, drivers also require an unobstructed view of the entire intersection, including any traffic control devices, and sufficient lengths along the intersecting highway to permit the driver to anticipate and avoid potential collisions with other vehicles. Thus, *intersection sight distance* (ISD) differs depending on the type of intersection and maneuver involved. The different types of ISD are summarized in the table below.

Design Guidelines

Case	Intersection Type and/or Maneuver	Sight Triangle	Sight Distance Determinant	Location in AASHTO (*1*)
A	Intersection with no control	Approach Triangle	Stopping sight distance with modified assumptions	Exhibit 9-51 Pg 655
B	Intersections with stop control on the minor road			
B1	Left turn from the minor road	Departure Triangle	Gap time equation	Exhibit 9-54 Pg 559
B2	Right turn from the minor road	Departure Triangle	Gap time equation	Exhibit 9-58 Pg 664
B3	Crossing maneuver from the minor road	Departure Triangle	Gap time equation	Exhibit 9-58 Pg 664
C	Intersections with yield control on the minor road			
C1	Crossing maneuver from the minor road	Approach Triangle	Stopping sight distance with modified assumptions	Exhibit 9-60 Pg 667
C2	Left turn from the minor road	Departure Triangle	Gap time equation	Exhibit 9-64 Pg 672
D	Intersections with traffic signal control	Both*	See Case D Guideline (*1*)	Pg 671
E	Intersections with all-way stop control	None	None required	Pg 674
F	Left turns from major road	Departure Triangle	Gap time equation	Exhibit 9-67 Pg 675

* First vehicle stopped on one approach should be visible to the driver of the first vehicle stopped on each of the other approaches and left-turning vehicles should have sufficient sight distance to select safe gaps in oncoming traffic.

The figure below shows the approach and departure triangles for different intersections/maneuvers.



Approach Triangles **Departure Triangles**

Discussion

The two types of sight triangles used in calculating ISD are described below.

Approach Sight Triangles: According to AASHTO (*1*), "Each quadrant of an intersection should contain a triangular area free of obstructions that might block an *approaching* driver's view of potentially conflicting vehicles. The length of the legs of this triangular area [shown as "a" and "b" in the figure on the opposing page], along both intersecting roadways, should be such that the drivers can see any potentially conflicting vehicles in sufficient time to slow or stop before colliding within the intersection." The vertex of the triangle that is nearest to the approaching driver represents the decision point at which the driver must begin to stop if the driver determines that a potential conflict is possible.

Departure Sight Triangles: According to AASHTO (*1*), departure sight triangles provide "sight distance sufficient for a stopped driver on a minor-road approach to depart from the intersection and enter or cross the major road." In this case, the vertex of the sight triangle is positioned over the driver of the stationary departing vehicle and the length of the triangle represents how far ahead the driver must be able to check for oncoming traffic that would make the maneuver unsafe. According to AASHTO (*1*), the length of the triangle is based on an *acceptable gap time* (which is independent of oncoming vehicle speed) that provides the departing vehicle with sufficient time to safely accelerate, cross the intersection and thus complete the maneuver. The gap time varies based on the vehicle type (e.g., passenger vehicle, combination truck, etc.) and distance that the vehicle must cross during the maneuver (e.g., number of lanes).

Design Issues

Although desirable at higher volume intersections, approach sight triangles are not necessary at intersections controlled by two-way and all-way stop controls or traffic signals because the stopping requirement is determined by the controls and not by approaching vehicles.

Departure sight triangles should be provided in each quadrant of the intersection approach controlled by stop or yield signs and for some signalized intersections (see Case D (*1*)). Also grade adjustments are recommended if the departing vehicle's rear wheels are on an upgrade that exceeds 3% at the stop line (*1*).

Cross References

Key Components of Sight Distance, 5-2
Determining Stopping Sight Distance, 5-4

Key References

1. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.

DETERMINING WHEN TO USE DECISION SIGHT DISTANCE

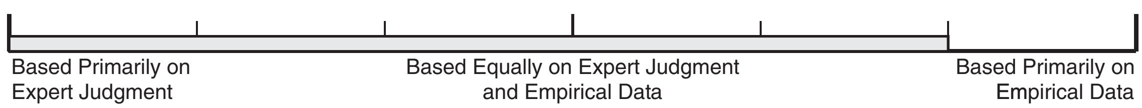
Introduction

According to AASHTO (*1*, page 115), *decision sight distance* (DSD) represents a longer sight distance than is usually necessary for situations in which (1) drivers must make complex or instantaneous decisions, (2) information is difficult to perceive, or (3) unexpected or unusual maneuvers are required. DSD provides drivers with additional safety margin for error and affords them sufficient length to maneuver their vehicles at the same or reduced speed, rather than to just stop.

The following time values (t) and equations (from AASHTO (*1*)) should be used to calculate decision time in the following situations:

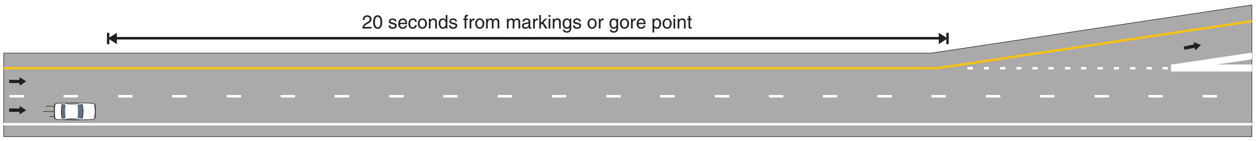
Avoidance Maneuver	A Stop on *Rural* Road	B Stop on *Urban* Road	C Speed/Path/ Direction Change on *Rural* Road	D Speed/Path/ Direction Change on *Suburban* Road	E Speed/Path/ Direction Change on *Urban* Road
Time (*t*)	*3.0 s*	*9.1 s*	*10.2–11.2 s*	*12.1–12.9 s*	*14.0–14.5 s*
Equation	**Metric**	**US Customary**	**Metric**		**US Customary**
	$d = 0.278Vt + 0.039\frac{V^2}{a}$	$d = 1.47Vt + 1.075\frac{V^2}{a}$	$d = 0.278Vt$		$d = 1.47Vt$
	t = time (see above) V = design speed (km/h) a = driver decel. (m/s^2)	t = time (see above) V = design speed (mi/h) a = *driver decel. (ft/s^2)*	t = time (see above) V = design speed (km/h)		t = time (see above) V = design speed (mi/h)
Common Examples	- Guide signs, traffic signals - Intersection where unusual or unexpected maneuvers are required - The paved area of an intersection for (1) first intersection in a sequence or (2) isolated rural intersections		- Lane markings indicating a change in cross section, overhead lane arrows - A change in cross section (lane drop, two lanes to four lanes, four lanes to two lanes, passing lane, climbing lane, optional lane split, deceleration lane, channelized right turn lane) - Lane closures in work zones		

- Time value *t* represents the sum of the PRT and MT components.
- Deceleration values for Maneuvers A and B can be taken from SSD guideline (page 5-4).

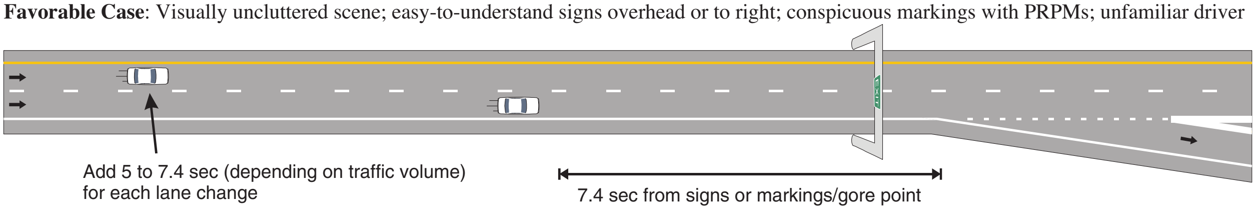


The figure below illustrates favorable and unfavorable conditions for Avoidance Maneuver E.

Unfavorable Case: Poor markings/signing, deceptive appearance of site, unexpected features (e.g., Freeway left exit);lane change required



Favorable Case: Visually uncluttered scene; easy-to-understand signs overhead or to right; conspicuous markings with PRPMs; unfamiliar driver



Discussion

Because some driving situations are particularly challenging (e.g., merging in moderate traffic during a lane drop), drivers require additional time to plan and execute the necessary maneuvers, or additional "safety margin" to compensate for errors they may make in the process. In these situations, use of DSD is appropriate because it incorporates the additional time that drivers need to complete more complicated driver actions. In particular, empirical data indicate that DSD is sufficiently long to accommodate the 85^{th} percentile values in most challenging driving situations, even for older drivers. The DSD time specifically provides more time so that drivers can do the following:

1. Detect an unexpected or difficult-to-perceive information source or condition in a roadway environment that may be visually cluttered (PRT)
2. Recognize the condition or its potential threat (PRT)
3. Select an appropriate speed and path (PRT)
4. Execute the appropriate maneuver safely and efficiently (MT)

In keeping with the components discussed in other sight distance guidelines (page 5-2), the first three of these tasks compose the PRT component while the fourth task is the MT component.

Although application of DSD is typically based on roadway features, certain situational factors can also adversely impact driver responsiveness. The frequent occurrence of the following factors at a site may indicate that the use of DSD is appropriate for that site:

- High driver workload due to concurrent tasks (e.g., traffic merging, reading signs)
- Truck traffic that intermittently blocks the view
- Off-roadway clutter that can distract drivers
- Poor weather that increases driver workload and makes cues (especially markings) less conspicuous
- High traffic volume levels

Design Issues

An important assumption when using DSD is that drivers are provided with and able to respond to signage that allows them to prepare in advance of the roadway feature. Studies indicate that when this advance information is not available or easy to miss, drivers may require additional time beyond the DSD. In these situations, driver responses are based on when they are able to see the actual roadway feature (e.g., turn arrow pavement marking, gore point), rather than on their perception of advance signage. In this situation, the 85^{th} percentile maneuver completion time (including the PRT) is between 20 and 23 s from the point at which the feature becomes visible (*2, 3*). Factors that may lead to these situations include the following:

- Dense traffic
- Poor marking and signing
- Deceptive appearance of site
- Features that violate driver expectancies (e.g., freeway left exit, add-drop lane)

Another design issue that warrants mention concerns lane changes. Additional sight distance may be necessary if drivers are expected to make multiple lane changes to complete a maneuver. In particular, each additional lane change adds an average of 5 s/lane in light traffic (≤ 725 vehicles/h) and 7.4 s/lane in medium-density traffic (726 to 1225 vehicles/h) to the maneuver.

Many design references use the term "design speed" to characterize the expected driving speed on a roadway. However, as noted in "Influence of Speed on Sight Distance" (page 5-12 of this document), neither design speed nor posted speed is always the best determinant of actual driving speed. When available, actual operating speeds should be used instead of design speed to help determine needed sight distance.

Cross References

Key Components of Sight Distance, 5-2
Determining Stopping Sight Distance, 5-4

Key References

1. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington DC.
2. Lerner, N., Huey, R.W., McGee, H.W., and Sullivan, A. (1995). *Older Driver Perception-Reaction Time for Intersection Sight Distance and Object Detection. Volume I, Final Report* (FHWA-RD-93-168). Washington, DC: FHWA.
3. McGee, H.W., Moore, W., Knapp, B.G., and Sanders, J.H. (1978). *Decision Sight Distance for Highway Design and Traffic Control Requirements* (FHWA-RD-78-78). Washington, DC: U.S. Department of Transportation.

DETERMINING PASSING SIGHT DISTANCE

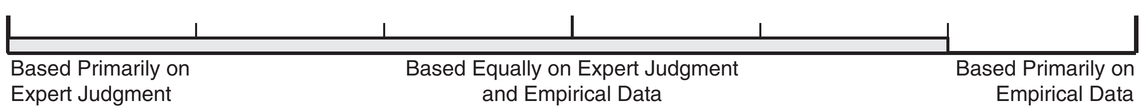
Introduction

According to AASHTO (*1*), *passing sight distance* (PSD) is how far ahead a driver must be able to see in order to complete a passing maneuver without cutting off the passed vehicle before meeting an opposing vehicle that appears during the maneuver. The guideline provides the design values for passes made at different speeds provided in AASHTO (*1*).

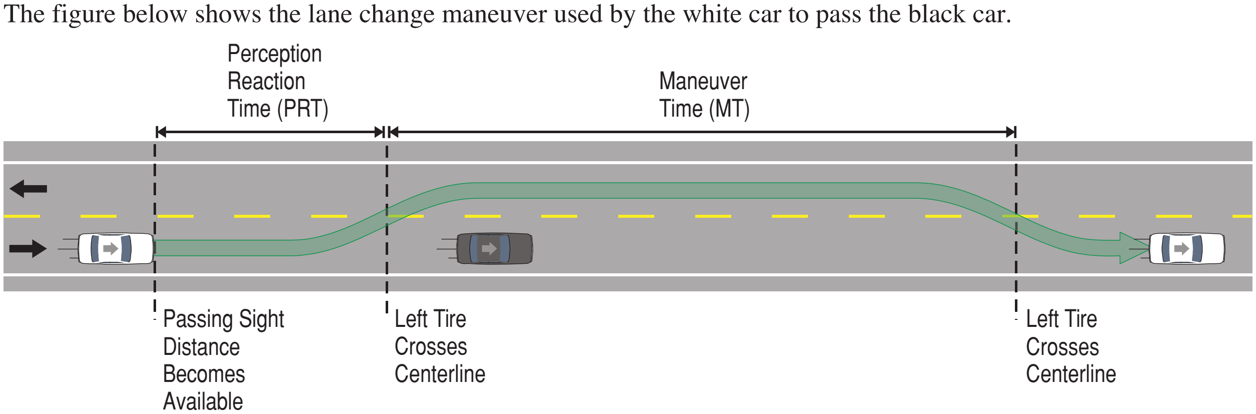
Design Guidelines

Metric				US Customary			
Design Speed (km/h)	Assumed Speeds (km/h)		Passing Sight Distance (m)	Design Speed (mi/h)	Assumed Speeds (mi/h)		Passing Sight Distance (ft)
	Passed Veh.	Passing Veh.			Passed Veh.	Passing Veh.	
30	29	44	200	20	18	28	710
40	36	51	270	25	22	32	900
50	44	59	345	30	26	36	1090
60	51	66	410	35	30	40	1280
70	59	74	485	40	34	44	1470
80	65	80	540	45	37	47	1625
90	73	88	615	50	41	51	1835
100	79	94	670	55	44	54	1985
110	85	100	730	60	47	57	2135
120	90	105	775	65	50	60	2285
130	94	110	815	70	54	64	2480
				75	56	66	2580
				80	58	68	2680

Note: The passing vehicle is assumed to be traveling 15 km/h or 10 mi/h faster than the passed vehicle.



The figure below shows the lane change maneuver used by the white car to pass the black car.



Discussion

The PSD encompasses both a PRT and an MT component. Mean PRTs to initiate a pass, measured from when PSD was available until when the **right** tire crossed the centerline, have been found to vary from 3.6 to 6.0 s, depending on the particular site on two-lane rural highways(*2*). No information is available on subject variability, but 85th percentile PRTs will certainly exceed mean reaction times. Just as other PRTs are affected by age, gender, standard transmissions, and day versus night conditions, PSD PRT may be as well; however, no studies were found on this issue. The primary cue that a driver uses to determine whether it is safe to initiate a pass is the size of the image of the oncoming vehicle. Research suggests that drivers make reasonable estimates of the distance of an oncoming car but not of its speed. This inability to reasonably estimate speed may be a more pronounced problem for older drivers.

MT is measured from the point at which either the left or right front tire (depending on study) of the subject vehicle crossed the centerline to the point at which the same front tire of the subject vehicle crossed the centerline back into the lane. One study found that on two-lane rural highways with approximately 96 km/h (60 mi/h) operating speeds and low traffic volumes (200 to 250 vehicles/h in the major direction and 85 to 175 vehicles/h in the minor direction), 65% to 75% of passes were attempted where there was no oncoming traffic, 25% to 35% of passes were attempted in the presence of oncoming traffic, and 0.8% of passes were aborted (*3*). In contrast, at high volumes (330 to 420 vehicles/h in the major direction and 70 to 170 vehicles/h in the minor direction), 51% to 76% of passes were made with no oncoming traffic, 26% to 50% of passes were in the presence of oncoming traffic, and 7.2 % of passes were aborted.

The average time in the opposing lane was 12.2 s under low traffic conditions and 11.3 s with high traffic volumes (based on when the front left tire—not the right tire as in the PRT case—entered and left the opposing lane). Depending on site and direction, times varied from a low of 8.0 s to a high of 12.9 s and there was no clear association between length of available passing lane and time spent in the opposing lane. At a speed of 96 km/h (60 mi/h) the average times in the opposing lane are equivalent to distances of 325 m (1064 ft) for low traffic and 301 m (986 ft) for high traffic.

Length of time spent in the passing lane is clearly related to the size of the time gap. In one study, drivers returning to their own lane with more than 10 s to spare averaged 12 s in the opposing lane. Drivers returning with 5 to 10 s to spare averaged 8.7 s and those with less than 5 s to spare, 6.8 s.

Drivers who pass may approach a slower vehicle and pass immediately (a flying pass), or may adopt a short headway and wait for an opportunity (a delayed pass). In the second case, more time for acceleration is required. In either case, drivers may adopt a short headway just prior to the pass. A study on two-lane highways found that 40% of drivers following at short headways (0.5 s or less) were doing so in anticipation of passing (*4*).

Design Issues

In passing situations, drivers' inaccurate estimates cannot be compensated for by increasing sight distance because the problem is that drivers misjudge the time they have to pass once they see the oncoming vehicle, and this problem remains the same regardless of how far down the road drivers can see. Instead, these types of crashes should be addressed through speed control measures or site factors that improve speed judgments.

Factors that increase the time needed to execute a passing maneuver include (1) a passenger vehicle passing multiple vehicles, (2) a passenger vehicle passing a truck, (3) a truck passing another vehicle, and (4) the passing occurring on an upgrade.

Many design references use the term "design speed" to characterize the expected driving speed on a roadway. However, as noted in "Influence of Speed on Sight Distance" (page 5-12 of this document), neither design speed nor posted speed is always the best determinant of actual driving speed. When available, actual operating speeds should be used instead of design speed to help determine needed sight distance.

Cross References

Key Components of Sight Distance, 5-2

Key References

1. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.
2. Hostetter, R.S., and Seguin, E.L. (1969). The effects of sight distance and controlled impedance on passing behavior. *Highway Research Record, 299*, 64-78.
3. Kaub, A.R. (1990). Passing operations on a recreational two-lane, two-way highway. *Transportation Research Record, 1280,* 156-162.
4. Rajalin, S., Hassel, S.-O., and Summala, H. (1997). Close following drivers on two-lane highways. *Accident Analysis & Prevention, 29*(6), 723-729.

INFLUENCE OF SPEED ON SIGHT DISTANCE

Introduction

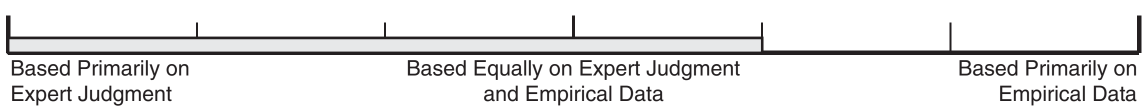
Although posted speed has been found to have the strongest association with operating speed, some visual aspects or driving-task demands associated with the roadway environment can "unconsciously" influence drivers' speed choice. Consequently, if operating speeds on a roadway significantly exceed design speed, sight distances on that roadway may be inadequate. In particular, drivers would have less time to react to an event or object at higher speed because they travel a greater distance during the initial PRT component of a response. Similarly, at higher speeds either vehicles take longer to stop/slow or maneuvers may become unsafe or overly difficult to perform.

Design Guidelines

If the operating speed of a roadway is substantially higher than the design speeds, increasing the sight distance to compensate for higher traveling speeds may be appropriate.

Examples of how design elements can cause operating speed to vary from design speed are shown in the table.

Design Element	Impact of Design on Speed
Lane Width	Increasing lane width from 3.3 to 3.8 m is associated with an increase of 2.85 km/h (1.78 mi/h) in speed on high design standard two-lane rural highways.
Alignment	Speed on curves can be reasonably accurately predicted using models based on radius, curve deflection angle, and curve length. Once the curve radius exceeds 800 m, curves have similar speeds to tangents. Speed on tangents is much more difficult to predict and depends on a wide array of road characteristics such as tangent length, radius of curve before and after the section, cross section, grade, general terrain, and sight distance. Posted speed is a better predictor of speed on urban arterial tangents than it is on highway tangents.
Pavement Surface	Some studies show pavement re-surfacing can be associated with a small (≈2 km/h) (1.25 mi/h) increase in speed.
Roadside Elements	Elements close to the edge of the lane (e.g., parked vehicles, foliage) contribute to a reduction in driver speed. Results of one study of road sections posted at 50 km/h (31 mi/h) showed that 85^{th} percentile speeds were 12 km/h (7.5 mi/h) lower in road sections with side friction due to the presence of pedestrians, bicyclists, parked vehicles, etc.



The table below describes the relationship between operating speed and design element from past studies (*1*).

OPERATING SPEED RELATIONSHIP WITH DESIGN ELEMENT

Element	Direct	Inconclusive	None
Sight Distance	Stopping sight distance[1]	Decision sight distance; passing sight distance; intersection sight distance	
Horizontal Alignment	Radius	Superelevation	
Vertical Alignment	Grades; climbing lanes	Vertical curves	
Cross Section	Lane width[2]; curb and gutter[3]; lateral clearance	Cross slope	Shoulder width
Other	Radii/tangent length combos[3]; number of lanes[4], median type; access density		

[1]with limits; [2]weak; [3]per one study; [4]freeways;

Discussion

The design of a road affects drivers' speeds through two major mechanisms. First, the design creates the driving task. Narrow lanes and sharp curves make the driving task more difficult and lead to reductions in speed. Second, drivers have expectations about the posted speeds—and comfortable speeds—based on various combinations of design elements. Users of this guide should be aware that operating speeds may be very different from posted speed when the road message and the posted speed are at variance. Thus design sight distances may be more appropriately determined based on operating, not posted, speed. The effects of different design features on speed are discussed below:

Lane Width: Lane width influences speed because it influences the difficulty of the driving task. Narrower lanes require more frequent, smaller steering corrections, which correspond to more effort. Slowing down reduces the effort required.

Alignment: Speed is strongly related to radius of curvature. Typically, models of predicted speed based on radius, deflection angle, and curve length account for more than 80% of the variance in speed. Similarly, one study of speeds in 176 curves on rural two-lane highways with posted speeds of 75 to 115 km/h found that V85 was most strongly related to radius and related, but less so, to grade and sight distance (R values .58 to .92) (*2*). Once the curve radius exceeded 800 m, curves had similar speeds to tangents. Speed on tangents is much more difficult to predict and is dependent on a wide array of road characteristics such as tangent length, radius of curve before and after the section, cross section, grade, general terrain, and sight distance. Accordingly, studies on urban arterials find posted speed limits typically account for only half of the variance in speed.

Pavement Surface: One of the cues drivers use to estimate their own speed is noise level. When sound cues were removed through the use of earmuffs, drivers underestimated their actual speeds by 6 to 10 km/h (*3*). Also, some studies suggest re-surfacing a road can result in a speed increase of 2 km/h.

Roadside Elements: Elements close to the edge of the lane—such as pedestrians, bicyclists, parked vehicles, and foliage—can strongly affect speed. One of the major cues used by drivers is the streaming of information in peripheral vision. Side friction increases the stimulus in peripheral vision, giving a sense of higher speed or greater hazard. In one study, drivers were asked to drive at 60 mi/h (96 km/h) with the speedometer covered. In an open-road situation, drivers averaged 57 mi/h (91 km/h). However, along a tree-lined route, drivers averaged 53 mi/h (85 km/h) (*4*). The trees, close by, provided peripheral stimulation, giving a sense of higher speed or greater hazard. The elements that create side friction—such as pedestrians, bicyclists, parked vehicles, and landscaping—also present various levels of hazard, likely influencing drivers to slow down to various degrees. In other words, pedestrian presence close to the road edge is more likely to affect speed than landscaping close to the road edge.

Design Issues

The relationship between several design elements and operating speed was investigated in a previous review of design elements (*1*). In some cases the relationship was found to be strong, such as for horizontal curves; however, for several other cases, such as lane width, the relationship was found to be weak. In all cases when a relationship between the design element and operation speed exists, there are ranges when the influence of the design element on speed is minimal.

Cross References

Key Components of Sight Distance, 5-2
Determining Stopping Sight Distance, 5-4
Determining Passing Sight Distance, 5-10

Key References

1. Fitzpatrick, K., Carlson, P.J., Brewer, M.A., Wooldridge, M.D., and Miaou, S.-P. (2003). *NCHRP Report 504: Design Speed, Operating Speed, and Posted Speed Practices.* Washington DC: Transportation Research Board.
2. Fitzpatrick, K., Carlson, P.J., Wooldridge, M.D., and Brewer, M.A. (2000). *Design Factors that Affect Driver Speed on Suburban Arterials* (FHWA/TX-001/1769-3). Washington, DC: FHWA.
3. Evans, L. (1970). Speed estimation from a moving automobile. *Ergonomics 13*, 219-230.
4. Shinar, D., McDowell, E., and Rockwell, T.H. (1977). Eye movements in curve negotiation. *Human Factors, 19(1),* 63-71.

KEY REFERENCES FOR SIGHT DISTANCE INFORMATION

Introduction

Sight distance requirements, issues, and subtopics have been covered extensively in a range of standard reference sources for roadway design and highway. It is important for roadway designers and traffic engineers to recognize that most of the information presented in this chapter has been adopted from these other sources and for users of this HFG to know where to go to find alternative sources of sight distance information.

Design Guidelines

The list below summarizes source and chapter for sight distance information from key reference sources:

A Policy on Geometric Design of Highways and Streets (2004)

Chapter 2, Design Controls and Criteria, discusses driver reaction time and related issues in Driver Performance subhead.

Chapter 3, Elements of Design, has a section on sight distance, with subsections on stopping sight distance, decision sight distance, passing sight distance, sight distance for multilane highways.

Chapters 5, Local Roads and Streets; 6, Collector Roads and Streets; 7, Rural and Urban Arterials; and 9, Intersections, all have a number of specific subsections on sight distance.

Manual on Uniform Traffic Control Devices (MUTCD) (2003)

MUTCD has several figures and tables relating minimum sight distance to speed, including Table 3B-1 (for passing sight distance), Table 4D-1 (for traffic control signal sight distance), Table 6C-2 (for work zone tapers), and Table 6E-1 (for work zone flagger stations).

Section 2C.05, Placement of Warning Signs, describes a PRT model. Tables 2C-4 (metric units) and 2C-5 (English units) show advance warning sign placement as a function of speed based on PRT requirements.

ITE Traffic Engineering Handbook (1999)

Chapter 2, Road Users, has sections on PRT and sight distance.

Chapter 11, Geometric Design of Highways, has a section on sight distance, with subsections on stopping sight distance, passing sight distance, decision sight distance, and intersection sight distance.

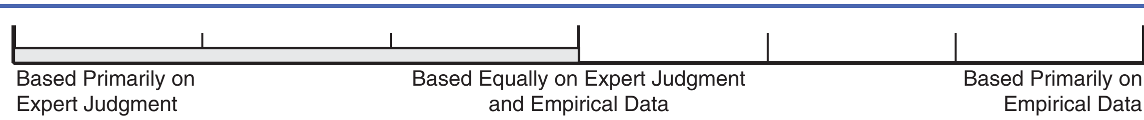
ITE Traffic Control Devices Handbook (2001)

Chapter 2, Human Factors, has sections on driver PRT and maneuver time.

Chapter 11, Highway-Rail Grade Crossings, contains discussion of sight distance requirements for at-grade crossings.

Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians (2001)

Sections on Intersections (I) and Roadway Curvature and Passing Zones (III) contain discussions of sight distance.



Discussion

The HFG focuses on key aspects of sight distance from the roadway users' perspective and is not intended to provide a comprehensive or definitive presentation of sight distance. Additional data sources follow:

A Policy on Geometric Design of Highways and Streets (*1*) provides guidance to roadway designers in the form of recommended values for a host of critical design dimensions. It is based on both established practices and standards, and reflects recent research. Most of the chapters contain sections or subsections that focus on user needs and characteristics; as noted above, Chapters 2, 3, 5, 6, 7, and 9 contain sight distance information.

The *Manual on Uniform Traffic Control Devices* (*2*) is the national standard for traffic control devices installed on any street, highway, or bicycle trail open to public travel. MUTCD provides uniform standards for the design of all signs, signals, markings, and other devices that are used to regulate, warn, or guide traffic and that are placed on, over, or adjacent to streets, highways, pedestrian facilities, and bikeways. Though MUTCD does not address sight distance issues as comprehensively as *A Policy on Geometric Design of Highways and Streets*, it does provide a number of very accessible and useful figures and tables on sight distance.

The *Traffic Engineering Handbook* (*3*) provides relevant key principles and techniques on "best" traffic engineering practices.

The *Traffic Control Devices Handbook* (*4*) is intended to augment and supplement the MUTCD by providing additional information and background information on selected topics. Although sight distance is not addressed as a separate chapter, PRT and MT are addressed in Chapter 2, Human Factors, and sight distance requirements for at-grade crossings are covered in Chapter 11, Highway-Rail Grade Crossings.

Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians (*5*) focuses on older roadway users but includes relevant information from key sources relating to sight distance (see also the accompanying handbook for these guidelines, published as FHWA-RD-01-103).

The *Highway Safety Manual* (under development, *6*) will also include various subsections addressing sight distance topics.

Design Issues

None

Cross References

Key Components of Sight Distance, 5-2
Determining Stopping Sight Distance, 5-4
Determining Intersection Sight Distance, 5-6
Determining When to Use Decision Sight Distance, 5-8
Determining Passing Sight Distance, 5-10
Influence of Speed on Sight Distance, 5-12

Key References

1. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington DC.
2. FHWA (2003). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.
3. Pline, J.L. (Ed.). (1999). *Traffic Engineering Handbook, Fifth Edition*. Washington, DC: ITE.
4. Pline, J.L. (Ed.). (2001). *Traffic Control Devices Handbook*. Washington, DC: ITE.
5. Staplin, L., Lococo, K., Byington, S., and Harkey, D. (2001) *Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians* (FHWA-RD-01-051). McLean, VA: FHWA, Research, Office of Safety R&D.
6. Hughes, W., Eccles, K., Harwood, D., Potts, I., and Hauer, E. (2004). *NCHRP Web Document 62: Development of a Highway Safety Manual*. Washington, DC: Transportation Research Board.

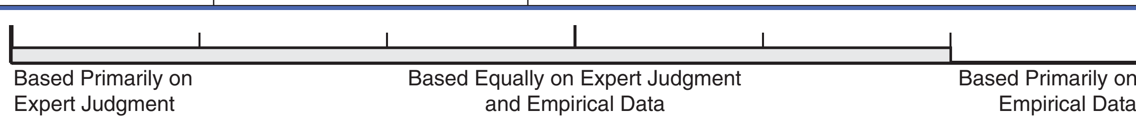
WHERE TO FIND SIGHT DISTANCE INFORMATION FOR SPECIFIC ROADWAY FEATURES

Introduction

The following table lists the information required to diagnose sight distance for specific roadway features. Although the roadway designer and the traffic engineer work with distances, sight distance needs actually originate from driver MT needs and speed choice. Therefore, to understand, diagnose, and address sight distance concerns, one must address the human factors issues of time and speed. Stopping sight distance is needed for all roadway features.

Design Guidelines

Feature or Problem	Type of Sight Distance Requirement	Information Required	Location of Information
All Roadway Features	Stopping sight distance	Operating speed	→ Determine
		Sight distance to hazard	→ Determine
		Required SSD	→ AASHTO, Exhibit 3-1 (*1*)
Horizontal Curve	Stopping sight distance	Operating speed	→ Determine
		Sight distance to hazard	→ Determine
		Required SSD	→ AASHTO, Exhibit 3-1 (*1*)
Horizontal Curve Approach with Warning Sign	Maneuver sight distance	Curve recommended speed	→ Determine
		Speed on approach	→ Determine
		Sign location	→ Determine
		Sign placement guidelines	→ MUTCD, Table 2C-4 (*2*)
Vertical Curve	Stopping sight distance	Operating speed	→ Determine
		Rate of vertical curvature, K	→ AASHTO, Exhibit 3-76 (*1*)
Vertical Curve	Passing sight distance	Operating speed	→ Determine
		Rate of vertical curvature, K	→ AASHTO, Exhibit 3-77 (*1*)
Warning Sign	Maneuver sight distance	Warning sign placement guidelines	→ MUTCD, Table 2C-4 (*2*)
Guide Sign	Maneuver sight distance	Typical placement of route signs	→ MUTCD, Figure 2D-6 (*2*)
Signed Lane Drop	Decision sight distance	Operating speed	→ Determine
		Avoidance maneuver C, D, or E	→ Determine
		DSD	→ AASHTO, Exhibit 3-3 (*1*)



Discussion

The sight distance diagnostic procedure consists of a systematic on-site investigation technique to evaluate the highway environment to support sight distance needs. The highway location is surveyed, diagrammed, and divided into component sections based on specific driving demands (e.g., need to perform a specific maneuver). Then each section is analyzed in terms of its suitability to support the required task (e.g., information provided to the driver, allotted time to complete the required task or maneuver). This procedure enables the practitioner to compare the available sight distance with the sight distance required to perform the driving task safely.

Procedures for measuring available sight distance are given in AASHTO (*1*) and the *Manual of Transportation Engineering Studies* (*3*). Available sight distance can be checked on plans for proposed designs or in the field for existing locations.

Design Issues

Many design references use the term "design speed" to characterize the expected driving speed on a roadway. However, as noted in "Influence of Speed on Sight Distance" (page 5-12 of this document), neither design speed nor posted speed is always the best determinant of actual driving speed. When available, actual operating speeds should be used instead of design speed to help determine needed sight distance.

Cross References

Tutorial 1: Real-World Driver Behavior Versus Design Models, 22-2
Tutorial 2: Diagnosing Sight Distance Problems and Other Design Deficiencies, 22-9

Key References

1. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.
2. FHWA (2003). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.
3. Robertson, H.D., Hummer, J.E., and Nelson, D.C.(Eds.) (2000). *Manual of Transportation Engineering Studies*. Washington, DC: ITE.

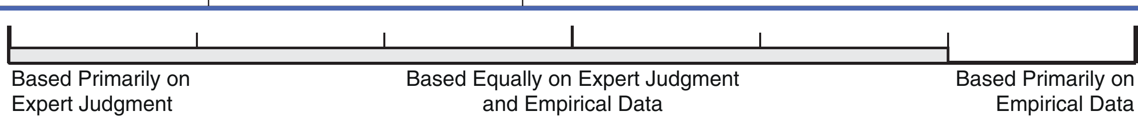
WHERE TO FIND SIGHT DISTANCE INFORMATION FOR INTERSECTIONS

Introduction

The following table lists the information required to diagnose sight distance at various intersection types. Although the roadway designer and the traffic engineer work with distances, sight distance needs actually originate from driver MT needs and speed choice. Therefore, to understand, diagnose, and address sight distance concerns, one must address the human factors issues of time and speed. Stopping sight distance is needed for all roadway features.

Design Guidelines

Feature or Problem	Type of Sight Distance Requirement	Information Required	Location of Information
Uncontrolled Intersection	Intersection sight distance	Sight triangle	→ Determine
		Operating speed	→ Determine
		Length of sight triangle legs	→ AASHTO, Exhibit 9-51 (*1*)
Two-Way Stop Intersection	Intersection sight distance	Operating Speed	→ Determine
	Case B1	ISD-Case B1	→ AASHTO, Exhibit 9-55 (*1*)
	Case B2	ISD-Case B2	→ AASHTO, Exhibit 9-58 (*1*)
	Case B3	ISD-Case B3	→ AASHTO, Exhibit 9-58 (*1*)
Intersection with Yield Control on Minor Road	Intersection sight distance	Operating Speed	→ Determine
	Case C1	ISD-Case C1	→ AASHTO, Exhibits 9-60 & 9-61 (*1*)
	Case C2	ISD-Case C2	→ AASHTO, Exhibit 9-64 (*1*)
Left turns from Major Road	Intersection sight distance—Case F	Time gap	→ AASHTO, Exhibit 9-66 (*1*)
		Operating speed	→ Determine
		ISD-Case F	→ AASHTO, Exhibit 9-67 (*1*)
Four-Way Stop Intersection	Intersection sight distance—Case E	None required	→ None required for ISD
Signalized Intersection	Intersection sight distance—Case D	None required for basic	→ None required for ISD signal operation
Roundabout	Stopping sight distance	Operating speed	→ Determine
		Required SSD	→ AASHTO, Exhibit 3-1 (*1*)
	Intersection sight distance	Sight triangle	→ Determine
		Length of conflicting leg	→ Roundabout Guide, Exhibit 6-33 (2)
Railroad-Highway Grade Crossing	RHGC sight distance sight triangle	Speed of vehicle	→ Determine
		Speed of train	→ Determine
	Case A	Distance from rail to stop line	→ Determine
	Case B	Required RHGC sight distance	→ AASHTO, Exhibit 9-104 (*1*)
Approach to Stop Condition	Decision sight distance	Operating speed	→ Determine
		Avoidance maneuver A or B	→ Determine
		DSD	→ AASHTO, Exhibit 3-3 (*1*)



Discussion

The sight distance diagnostic procedure consists of a systematic on-site investigation technique to evaluate the highway environment to support sight distance needs. The highway location is surveyed, diagrammed, and divided into component sections based on specific driving demands (e.g., need to perform a specific maneuver). Then each section is analyzed in terms of its suitability to support the required task (e.g., information provided to the driver, allotted time to complete the required task or maneuver). This procedure enables the practitioner to compare the available sight distance with the sight distance required to perform the driving task safely.

Procedures for measuring available sight distance are given in AASHTO (*1*) and Robertson, Hummer, and Nelson, (*4*). Available sight distance can be checked on plans for proposed designs or in the field for existing locations. Tustin, Richards, McGee, and Patterson (*3*) and Robertson et al. (*4*) provide additional information that may be useful for determining sight distance.

Design Issues

Many design references use the term “design speed” to characterize the expected driving speed on a roadway. However, as noted in “Influence of Speed on Sight Distance” (page 5-12 of this document), neither design speed nor posted speed is always the best determinant of actual driving speed. When available, actual operating speeds should be used instead of design speed to help determine needed sight distance.

Cross References

Tutorial 1: Real-World Driver Behavior Versus Design Models, 22-2
Tutorial 2: Diagnosing Sight Distance Problems and Other Design Deficiencies, 22-9

Key References

1. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.
2. FHWA (2000). *Roundabouts: An Informational Guide* (Publication FHWA-RD-00-067). Washington, DC.
3. Tustin, B., Richards, H., McGee, H., and Patterson, R. (1986). *Railroad-Highway Grade Crossing Handbook, Second Edition* (FHWA-TS-86-215). Fairfax, VA: Tustin Enterprises.
4. Robertson, H.D., Hummer, J.E., and Nelson, D.C. (2000). *Manual of Transportation Engineering Studies*. Washington, DC: ITE.

CHAPTER 6

Curves (Horizontal Alignment)

Forthcoming

CHAPTER 7

Grades (Vertical Alignment)

Forthcoming

CHAPTER 8

Tangent Sections and Roadside (Cross Section)

Forthcoming

CHAPTER 9

Transition Zones Between Varying Road Designs

Forthcoming

CHAPTER 10

Non-Signalized Intersections

ACCEPTABLE GAP DISTANCE

Introduction

Acceptable gap distance refers to the size of the gaps in major-road traffic typically accepted by drivers turning from a minor road that provide sufficient time for the minor-road vehicle to accelerate from stop and complete a turn without unduly interfering with major-road traffic operations. A constant-value of time gap, independent of approach speed, can be used for determining intersection sight distance (see AASHTO (*1*)). In particular, the intersection sight distance in both directions should be equal to the distance traveled at the design speed of the major road during a period of time equal to the gap.

Design Guidelines

Design Vehicle	Time Gap (t_g) at Design Speed of Major Road	
	Left Turn	**Right Turn**
Passenger Car	7.5 s	6.5 s
Single-Unit Truck	9.5 s	8.5 s
Combination Truck	11.5 s	10.5 s

Note: Time gaps are for a stopped vehicle to turn onto a two-lane highway with no median and grades of 3% or less. The table values require adjustment as follows:

For multilane highways:

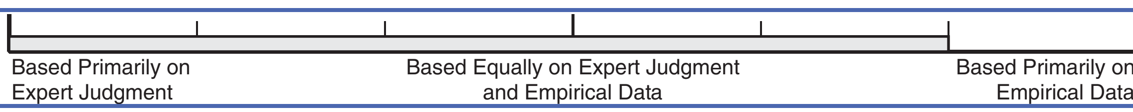
For turns onto highways with more than two lanes, add 0.5 s for passenger cars or 0.7 s for trucks for each additional lane (including narrow medians that cannot store the design vehicle), in excess of one, to be crossed by the turning vehicle.

For *left* turn onto minor roads with approach grades:

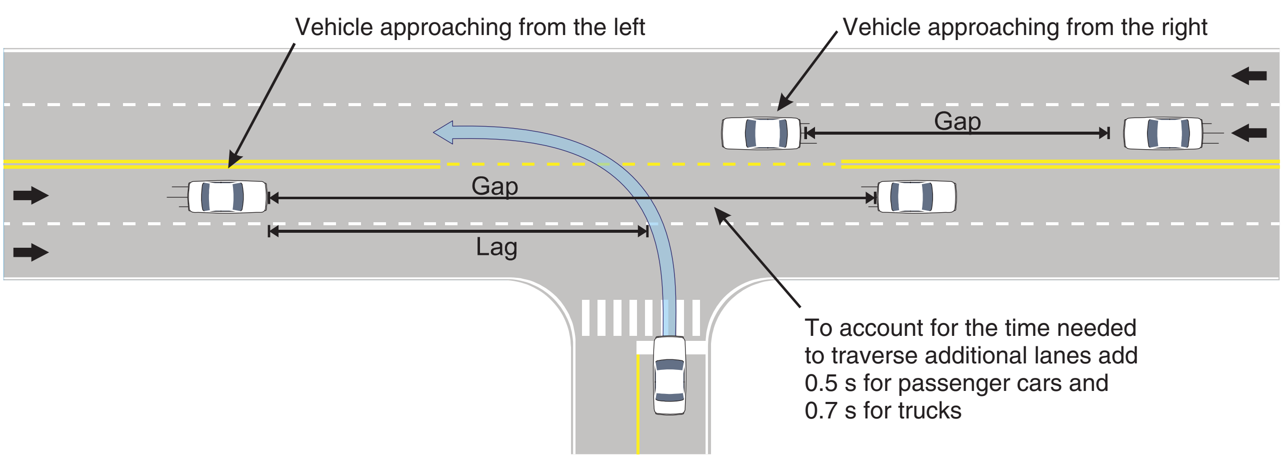
If the approach grade is an upgrade that exceeds 3%, add 0.2 s for each percent grade.

For *right* turn on minor roads with approach grades:

If the approach grade is an upgrade that exceeds 3%, add 0.1 s for each percent grade.



The figure below shows the different aspects of gap acceptance in a left-turn situation. Gaps are defined as the time interval between two successive vehicles, measured from the rear of a lead vehicle to the front of the following vehicle. Lags are defined as the time interval from the point of the observer to the arrival of the front of the next approaching vehicle.



Discussion

Safe gap acceptance distances depend on the driver's ability to accurately judge the time available to execute a traffic-crossing maneuver. Chovan, Tijerina, Everson, Pierowicz, and Hendricks (*2*) indicate that failure to accurately perceive and judge safe gap distances can have serious safety consequences, and that two of the most common causal factors for left turn crashes are misjudged gap/velocity (30% to 36% of crashes) and drivers misperceiving (e.g., "looked but did not see") oncoming traffic (23% to 26% of crashes).

At short distances, where the size of the visual image (on the observer's retina) of the oncoming traffic is relatively large, time-to-arrival judgments may be made based on optical properties of the scene, such as the observed rapid expansion ("looming") of the visual image as the object approaches (see, for example, Kiefer, Cassar, Flannagan, Jerome, and Palmer (*3*)). However, at the distances involved in roadway gap judgments there is less agreement about whether these optical properties are as important or if other aspects, such as speed and distance judgments, dominate. In general, however, observers are not particularly adept at making judgments about arrival time and they tend to underestimate this value by 20% to 40% (*4*). Fortunately, the degree of underestimation is reduced with higher oncoming vehicle speed and with longer viewing duration (*4*).

One study found that distance from oncoming vehicle was the best predictor of gap acceptance, while vehicle speed and time-to-arrival were weaker predictors (*5*). This finding suggests that drivers are somewhat insensitive to oncoming vehicle speed, which means that they may be more likely to accept smaller/less-safe gaps if the speeds of oncoming vehicles are higher. Also, this effect appears to be more pronounced in older drivers than in younger drivers (*6*).

The data for the acceptable gap distance guideline come from Harwood, Mason, and Brydia (*7*), which measured critical gap for use as an intersection sight distance criterion. For design purposes, the critical gap represents the gap between successive oncoming vehicles that average drivers will accept 50% of the time (and reject 50% of the time). The rationale for using critical gap as an ISD criterion is that if drivers will accept a specific critical gap in the major-road traffic stream when making a turning maneuver, then sufficient ISD should be provided to enable drivers to identify that critical gap. The key findings from Harwood et al. (*7*), which are reflected in the guideline, are that drivers accept slightly shorter gaps for right turns than for left turns, and that heavy vehicles require longer gaps. Note, however, that other studies have not found a difference in gap acceptance size based on turn direction. In particular, one study found that passenger vehicle drivers accepted a critical gap of 6.5 s for both left and right turns; this source also reviewed comparable studies that also found mixed results regarding the effect of turn direction (*8*). Another factor that must be considered is the direction from which drivers face conflicting traffic. In particular, Kittelson and Vandehey (*9*) found that left-turning drivers will accept shorter gaps if the gap they are evaluating involves a vehicle approaching from the left rather than from the right.

Design Issues

Vehicles approaching the turning/crossing vehicle can be expected to slow down to avoid any potential conflicts; however, this deceleration may impact capacity on high-volume roadways. Harwood et al. (*7*) found that for turns executed with gaps of less than 10 s, oncoming vehicles decelerated from 0% to 80% with a median deceleration of 31% (average deceleration level was 0.68 m/s^2). On average, two-thirds of the speed reduction occurs before the oncoming vehicle reaches the intersection. The average acceleration level of the turning vehicle was 1.46 m/s^2.

Cross References

Determining Intersection Sight Distance, 5-6
Factors Affecting Acceptable Gap, 10-4

Key References

1. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington DC.
2. Chovan, J., Tijerina, L., Everson, J., Pierowicz, J., and Hendricks, D. (1994). *Examination of Intersection, Left Turn Across Path Crashes and Potential IVHS Countermeasures* (DOT HS 808 154). Washington, DC: National Highway Traffic Safety Administration.
3. Kiefer, R.J., Cassar, M.T., Flannagan, C.A., Jerome, C.J., and Palmer, M.D. (2005). *Surprise Braking Trials, Time-to-Collision Judgments, and "First Look" Maneuvers under Realistic Rear-End Crash Scenarios* (Forward Collision Warning Requirements Project, Tasks 2 and 3a Final Report, DOT HS 809 902). Washington, DC: National Highway Traffic Safety Administration, Office of Advanced Safety Research.
4. Groeger, J.A. (2000). *Understanding Driving: Applying Cognitive Psychology to a Complex Everyday Task*. Hove, U.K.: Psychology Press.
5. Davis, G.A., and Swenson, T. (2004). Field study of gap acceptance by left-turning drivers. *Transportation Research Record, 1899*, 71-75.
6. Staplin, L. (1995). Simulator and field measures of driver age differences in left-turn gap judgments. *Transportation Research Record, 1485,* 49-55.
7. Harwood, D.W., Mason, J.M., Jr., and Brydia, R.E. (2000). Sight distance for stop-controlled intersections based on gap acceptance. *Transportation Research Record, 1701*, 32-41.
8. Fitzpatrick, K. (1991). Gaps accepted at stop-controlled intersections. *Transportation Research Record, 1303*, 103-112.
9. Kittelson, W.K., and Vandehey, M.A. (1991). Delay effects on driver gap acceptance characteristics at two-way stop-controlled intersections. *Transportation Research Record, 1320*, 154-159.

FACTORS AFFECTING ACCEPTABLE GAP

Introduction

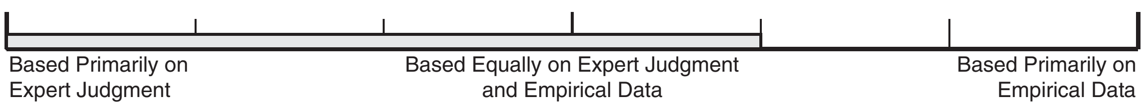
The *factors affecting acceptable gap* refer to the driver, environment, and other situational factors that cause most drivers or specific groups of drivers (e.g., older drivers) to accept smaller or larger gaps than they would otherwise accept under normal conditions. These guidelines only apply when there is no center median or acceleration lane that provides shelter to the turning vehicle.

Design Guidelines

Certain driver, environmental, or situational factors can systematically influence driver gap acceptance behavior. If these factors are common at an intersection location, then consideration should be given to modifying the gap acceptance design assumptions.

Factor	Finding	Data Quality*
Driver Age	Older drivers accept a critical gap that is approximately 1 s longer than younger drivers, and they reject more acceptable gaps overall.	●
Wait Times	Critical gap size decreases as a function of time spent waiting at the stop line.	●
Direction of Turn	Drivers will accept shorter gaps if the primary conflicting vehicle is approaching from the driver's left than if it is from the driver's right (same destination lane).	●
Familiarity with Roadway	Drivers on familiar routes (e.g., work commutes) accept smaller critical gaps.	○
Oncoming Vehicle Size	Larger vehicles are perceived as arriving sooner than smaller vehicles.	○
Traffic Volume	Drivers accept smaller gaps with higher major-road traffic volume.	○
Headlight Glare	Drivers accept longer critical gaps with oncoming headlight glare.	○

*Data Quality: ● = established finding; ○ = some empirical evidence, but magnitude of effect and reliability of findings are unconfirmed.



The table below shows the perceptual, cognitive, and psychomotor subtasks associated with the key activities that drivers must perform when making left or right turns across traffic in a four-lane roadway (adapted from Richard, Campbell, and Brown (*9*)).

Activity	Perceptual Subtasks	Cognitive Subtasks	Psychomotor Subtasks
1. Check for possible conflicts with following vehicle.	Visually assess trajectory of following vehicle.	Determine if distance and speed of vehicle indicate potential conflict.	Head and eye movements to observe rearview mirror.
2. Check for pedestrians/cyclists crossing or about to cross in front.	Look left and right along crosswalk.	Determine if pedestrians/cyclists are present or likely to enter the crosswalk.	Head and eye movements for viewing.
3. Advance into crosswalk.	Visually observe crosswalk.	Determine when vehicle is in appropriate position for turning.	Slowly accelerate and brake.
4. Look for gap in perpendicular traffic.	Visually monitor traffic.	Determine distance and speed of oncoming traffic. Determine if gap is sufficient for turning.	Head and eye movements to monitor oncoming traffic.
5. Check for oncoming vehicles in far lane changing to destination (conflicting) lane.	Monitor oncoming vehicles in far lane.	Determine if vehicle is about to change lanes (e.g., turn signal on, changing trajectory, etc.).	Head and eye movements to monitor oncoming traffic.
6. Check for hazards in turn path.	Visually scan turn path (especially crosswalk) and intended lane.	Determine if any pedestrians/cyclists or other hazards are in the crosswalk or about to enter.	Head and eye movements to view turn path.
7. Accelerate to initiate turn.	View roadway.	Determine that acceleration is sufficient to avoid conflicts with other vehicles	Quickly accelerate. Head and eye movements.
8. Steer into turn.	View turn path.	Determine that vehicle trajectory and lane position are appropriate.	Steering adjustments necessary to stay in lane.

Discussion

Driver age: Several studies have found that older drivers require gaps that are approximately 1 s longer than younger drivers. Some studies also find that older drivers tend to reject more usable gaps than other drivers, which leads to capacity reductions (*1, 2*). The data suggest that these differences likely reflect more cautious decision criteria (*1*). Yi (*2*) also found that older drivers require more time to enter and accelerate to the desired speed (10–13 s to reach 25 mi/h and 16–19 s to reach 35 mi/h compared to the respective 7–9 s and 12–14 s for younger drivers).

Wait times: Most vehicles that wait in a queue accept smaller gaps than those that do not wait (*3*). Also, the longer that drivers wait, the more likely they are to accept gaps that they previously rejected as being too short (*4*). Note that there is no information about whether this arises from increased driver frustration or from drivers learning through observation that smaller gaps are likely to be safe (*3*).

Direction of turn: Drivers accept shorter gaps if the primary other vehicle is approaching from the driver's left than if it is approaching from the driver's right (*4, 5*). For example, a driver making a left turn will accept a smaller gap from a vehicle approaching from the left (for which there will only be a conflict while the turning vehicle crosses its path), than one approaching from the right (for which there will be a potential conflict until the turning vehicle gets up to speed). If drivers are faced with a single vehicle coming in the conflicting direction, then some data suggest that drivers will accept shorter gaps while making right turns than left turns (*6*); however, there is also evidence that this difference is small or insignificant.

Familiarity with the roadway: Only one study considered the effects of driver familiarity on gap acceptance (*5*). This study found that drivers on regular commute trips generally accept smaller gaps, which seems to arise because drivers are familiar with what constitutes a safe gap in a particular turn situation.

Oncoming vehicle size: Some driving simulator research indicates that larger vehicles are perceived as arriving sooner than smaller vehicles, even if their actual arrival time is the same (*7*). This finding may have implications for roadways with high motorcycle traffic, because drivers may overestimate the gap size for these smaller vehicles.

Traffic volume: Higher traffic volume on the major road appears to lead to drivers accepting smaller gaps (*3*). This situation could arise because large gaps are less common or drivers see the need to take whatever gap is available, even if it is smaller than what they would normally take.

Headlamp glare: Data from a study involving unlit rural conditions indicated that accepted gaps were significantly larger under higher glare conditions from approaching vehicles, although the lighting systems used were from the late 1960s and therefore the data may be less applicable today (*8*).

Design Issues

None.

Cross References

Determining Intersection Sight Distance, 5-6
Acceptable Gap Distance, 10-2

Key References

1. Lerner, N., Huey, R.W., McGee, H.W., and Sullivan, A. (1995). *Older Driver Perception-Reaction Time for Intersection Sight Distance and Object Detection. Volume I, Final Report*. (FHWA-RD-93-168). Washington, DC: FHWA.
2. Yi, P. (1996). Gap acceptance for elderly drivers on rural highways. *Compendium of Technical Papers for the 66th ITE Annual Meeting* (pp. 299-303). Washington, DC: ITE.
3. Kyte, M., Clemow, C., Mahfood, N., Lall, B.K., and Khisty, C.J. (1991). Capacity and delay characteristics of two-way stop-controlled intersections. *Transportation Research Record, 1320*, 160-167.
4. Kittelson, W.K., and Vandehey, M.A. (1991). Delay effects on driver gap acceptance characteristics at two-way stop-controlled intersections. *Transportation Research Record, 1320*, 154-159.
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8. Tsongos, N.G., and Schwab, R.N. (1970). Driver judgments as influenced by vehicular lighting at intersections. *Highway Research Record, 336*, 21-32.
9. Richard, C.M., Campbell, J.L., and Brown, J.L. (2006). *Task Analysis of Intersection Driving Scenarios: Information Processing Bottlenecks* (FHWA-HRT-06-033). Washington, DC: FHWA.

SIGHT DISTANCE AT LEFT-SKEWED INTERSECTIONS

Introduction

Sight distance at left-skewed intersections refers to the available sight distance to the driver's right side for a vehicle crossing a major road from a left-skewed minor road (where the acute angle is to the right of the vehicle). In left-skewed intersections, the driver's line of sight can be obstructed by parts of the driver's vehicle, such as the roof posts, door frame, passenger-seat headrest, or a panel aft of the door. This obstruction is most likely to occur for vehicles that have vision-restricting rearward elements, for example, ambulances, motor homes, truck tractors with sleeping areas, single-unit trucks, and school buses. These sight-line restrictions can result in reduced sight distances because the driver cannot see as far down the intersecting road as with 90° intersections. AASHTO (*1*) recommends that intersection angles be skewed no more than 60°; however, as Gattis and Low (*2*) indicate, intersections that are skewed from 60° to 70° can still result in insufficient sight distance for vision-restricted vehicles at certain design speeds.

The guideline provides information about available sight distance (ASD) and the design speed that accommodates the ASD for different viewing/vision angles. Two different vision angle conditions are presented. The minimum vision angle indicates design parameters for the minimum recommended vision angle. The desirable vision angle provides more conservative recommended values that better accommodate larger vehicles and older drivers.

Design Guidelines

Design speeds for the major roadway should be consistent with available sight distance for the minor-road vehicle based on at least the minimum vision angle viewing position, but use of the desirable vision angle is preferable and better accommodates larger vehicles and older drivers.

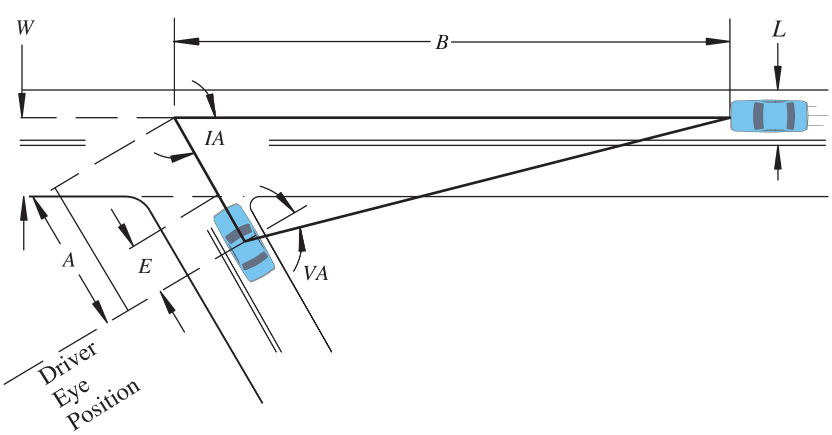
RESULTING AVAILABLE SIGHT DISTANCE FOR 5.4-M AND 4.4-M SETBACKS*

Intersection Angle (degrees)	Resulting ASD for a 5.4-m Setback				Resulting ASD for a 4.4-m Setback			
	Minimum Vision Angle: 13.5°		Desirable Vision Angle: 4.5°		Minimum Vision Angle: 13.5°		Desirable Vision Angle: 4.5°	
	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)
55	31.8	31	23.6	<30	–	–	–	–
60	39.8	37	26.9	<30	36.4	35	24.6	<30
65	55.4	46	32.3	32	50.5	43	29.5	30
70	95.7	65	41.6	38	87.1	61	37.8	36
75	408.2	>120	60.1	49	371.1	>120	54.6	46

**Calculations assume a W (see figure below) of 5.4 based on 1½ lane widths of 3.6 m.*

Based Primarily on Expert Judgment — Based Equally on Expert Judgment and Empirical Data — Based Primarily on Empirical Data

The figure below shows the variables and dimensions used to calculate the ASD and design speed values in the table.



A	Subject Vehicle (SV) Collision Distance
E	Setback Distance
B	Available Sight Distance
IA	Intersection Skew Angle
VA	Subject Vehicle Vision Angle
W	Distance from Principal Other Vehicle (POV) to Intersection Tangent Line
L	Lane Width (3.6 m)

Discussion

The available sight distances presented in the guideline are calculated based on drivers of restricted-vision vehicles viewing oncoming traffic backwards over their right shoulder. The 4.5° viewing-angle condition represents a driver sitting back fully against the seat, which represents the most restricted viewing-angle condition. Actual viewing angles from this position can range from around 2° in ambulances and motor homes to 7° or 8° in single-unit trucks and school buses. Viewing angles are typically more than 19° in all vehicles if drivers adopt an extreme "leaning forward" position in which their head is positioned almost directly above the steering wheel (*2*). The 13.5° viewing-angle condition used in the guideline represents an intermediate "leaning forward" driver posture that is between the "fully against the seat back" position and the "full forward" position. It was selected based on expert judgment of a review panel involved in the study and represents a reasonable approximation of how far forward most drivers could be expected to lean.

Son, Kim, and Lee (*3*) measured the available vision angle in three Korean design vehicles (passenger cars, single-unit trucks, and semi-trailers). The viewing angles in single-unit trucks and semi-trailers were 1.3° in the "seat back" position and 12.6° to 13.1° in the "full forward" position. However, viewing angles from a comfortable "leaning forward" position in these vehicles were 5.2° to 5.4°, which are smaller than the 13.5° viewing angle adopted for the guideline. Viewing angles for passenger cars were much greater, having values of 13.5° and 17° in the "seat back" and comfortable "leaning forward" positions, respectively.

It should be noted that some drivers, especially older drivers, may be restricted in their ability to lean forward because of limitations in their neck and trunk flexibility, and therefore the intermediate "leaning forward" position (13.5°) may be difficult to obtain. If the design must accommodate older drivers, use of the desirable vision angle may be more appropriate. See the guideline "Sight Distance at Right-Skewed Intersections" for additional discussion of this issue.

The design speed measure reported in the guideline is based on the time available for the vehicle on the major road to stop or avoid a conflict with the minor-road vehicle that entered the intersection late based on what its driver could see from the restricted viewing angle. Note that vehicles passing through skewed intersections also have a longer distance to traverse, which increases the driver's exposure to oncoming traffic.

The 5.4-m setback represents a conservative estimate for how far back the driver's eye position is from the edge of the major road. More specifically, it is based on the distance of 5.4 m measured from the minor-road vehicle driver's eye to the edge of the cross road. This value is the recommended driver-position setback for intersection sight distance calculations (*4*). However, a setback distance of 4.4 m may also be used for constrained situations and is consistent with driver behavior in response to restricted sightline situations.

Design Issues

To what extent the current recommendations apply to light trucks is uncertain at this point. Restricted rearward viewing may occur with light trucks because some lack a rear seating area with windows and some have truck bed attachments that can obscure the rearward view.

Cross References

Determining Intersection Sight Distance, 5-6
Sight Distance at Right-Skewed Intersections, 10-8

Key References

1. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington DC.
2. Gattis, J.L. and Low, S.T. (1998). Intersection angle geometry and the driver's field of view. *Transportation Research Record, 1612*, 10-16.
3. Son, Y.T., Kim, S.G., and Lee, J.K. (2002). Methodology to calculate sight distance available to drivers at skewed intersections. *Transportation Research Record, 1796*, 41-47.
4. Harwood, D.W., Mason, J.M., Brydia, R.E., Pietrucha, M.T., and Gittings, G.L. (1996). Appendix H: Field studies of vehicle dimensions and vehicle-stopping positions on minor-road approaches to stop-controlled intersections. Contractor's Final Report, NCHRP Project 15-14(1).Washington, DC: Transportation Research Board.

SIGHT DISTANCE AT RIGHT-SKEWED INTERSECTIONS

Introduction

Sight distance at right-skewed intersections refers to the available sight distance to the driver's left side for a vehicle crossing a major road from a right-skewed minor road (where the acute angle is to the left of the vehicle). In right-skewed intersections, the drivers' line of sight over their left shoulder is not typically obstructed by parts of their vehicle, such as the case with left-skewed intersections. In contrast, the primary limitations to drivers' line of sight are their ability to physically turn their body to the left and how far over their shoulder they can orient their gaze to view oncoming vehicles. These viewing limitations can result in reduced sight distances because the driver can not see as far down the intersecting road as they could at a 90° intersection. The guideline provides recommendations for accommodating older drivers who are more likely to have neck and/or trunk movement restrictions, in addition to recommendations for drivers without such limitations (identified as "other drivers").

Design Guidelines

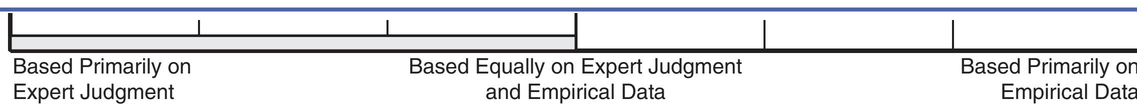
Design speeds for the major roadway should be consistent with available sight distance (ASD) for the minor-road vehicle based on at least the vision angle for drivers without neck and/or trunk movement restrictions (other-driver); however, the use of the older-driver vision angle better accommodates older drivers and those drivers with neck and/or trunk movement restrictions regardless of age.

RESULTING AVAILABLE SIGHT DISTANCE FOR 5.4-M AND 4.4-M SETBACKS*

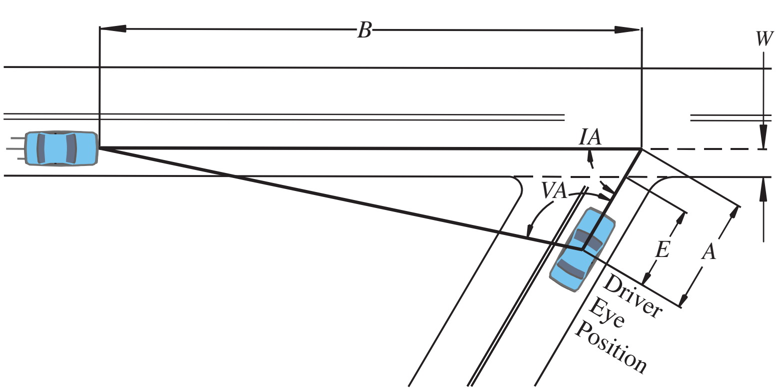
Intersection Angle (degrees)	Resulting ASD for a 5.4-m Setback				Resulting ASD for a 4.4-m Setback			
	Other-Driver Vision Angle: 115°		Older-Driver Vision Angle: 95°		Other-Driver Vision Angle: 115°		Older-Driver Vision Angle: 95°	
	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)	ASD (m)	Design Speed (km/h)
55	39.7	35.8	15.1	17.0	35.0	32.7	13.3	15.3
60	77.8	57.4	17.6	19.2	68.4	52.7	15.5	17.3
65	Not limited†	>120	21.5	22.6	Not limited†	>120	18.9	20.3
70	Not limited†	>120	28.2	27.8	Not limited†	>120	24.7	25.1
75	Not limited†	>120	41.7	37.2	Not limited†	>120	36.5	33.7

**Calculations assume a W (see figure below) of 1.8 based on ½ a lane width of 3.6 m.*

†At higher intersection angles, driver visibility is not limited by vision angle.



The figure below shows the variables and dimensions used to calculate the ASD and design speed values used in the guideline table.



A	Subject Vehicle (SV) Collision Distance
E	Setback Distance
B	Available Sight Distance
IA	Intersection Skew Angle
VA	Subject Vehicle Vision Angle
W	Distance from Principal Other Vehicle (POV) to Intersection Tangent Line

Discussion

The primary limiting factor for visibility with right-skewed intersections is the drivers' direct field of view based on how far over their left shoulder they can see by turning their body, head, and eyes to the left. This visibility limitation contrasts with left-skewed intersections, in which parts of the vehicle body can obstruct the drivers' view over their right shoulder regardless of how far they can see to the side. Difficulty with head turning was one of the most frequently mentioned concerns in older-driver focus groups, and these drivers reported experiencing difficulty turning their heads at angles less than 90° to view traffic on intersecting roadways. Moreover, joint flexibility declines by an estimated 25% in older drivers because of arthritis, calcification of cartilage, and joint deterioration (*1*). If roadway designers need to consider older-driver capabilities in the design of skewed intersections, then use of the older-driver vision angle values from the guideline is recommended.

The values in the guideline table provide estimated ASD and recommended design speed for oncoming vehicles based on approximations of how far to the left drivers on the minor road can be expected to see. The ASD and design speed values in the guideline table were computed using an analogous approach to the one taken in the guideline "Sight Distance at Left-Skewed Intersections," which is based on Gattis and Low (*5*). Specifically, these terms represent the time available for a vehicle on the major road to stop or avoid a conflict with the minor-road vehicle that entered the intersection based on what its driver could see from the restricted viewing angle.

The minor-road driver's viewing angle is calculated using estimated trunk, head, and eye movement capabilities observed in healthy young and middle-aged drivers (other-driver vision angle) and healthy older drivers (older-driver vision angle). For the other-driver vision angle, trunk, neck, and eye movement values of 30°, 70°, and 15° (totaling 115°) were used. For the older-driver vision angle, trunk, neck, and eye movement values of 25°, 55°, and 15° (totaling 95°) were used.

No data are currently available on trunk rotation range for seated drivers restrained by safety belts. The trunk rotation value used in the guideline calculations was based on an estimate of comfortable trunk rotation range for a restrained non-older driver of 30°, and then reduced by 5° to represent reduced flexibility in older drivers.

The neck rotation values are based on the study by Isler, Parsonson, and Hansson (*2*), which measured neck rotation to the left in seated drivers. In this study, 80% of drivers aged 59 years or younger had a neck movement range of 70° or more, while 75% of drivers aged 60 or older had a neck movement range of 55° or more. Note that these values are greater than those reported in another more comprehensive study of neck rotation, which found *mean* neck rotation to the left to be 65° in healthy people aged 20 to 59, and 54° in healthy people aged 60 to 79 (*3*).

The guideline table also assumes that drivers are able to execute at least one eye movement 15° toward the left. There are no data indicating how far drivers will move their eyes when making judgments about oncoming vehicle approaches; however, most naturally occurring eye movements (saccades) have an amplitude of 15° or less, and eye movements longer than this are effortful (*4*). While this 15° value may be considered as representing a conservative eye movement amplitude, many older drivers have limited peripheral vision, which would make it difficult to efficiently move their eyes farther out than 15° (*2*).

Design Issues

The estimates of how far drivers can see to their left contain some degree of uncertainty, because of the lack of reliable information on driver trunk rotation and eye movement amplitude.

Cross References

Determining Intersection Sight Distance, 5-6
Sight Distance at Left-Skewed Intersections, 10-6

Key References

1. Staplin, L., Lococo, K., Byington, S., and Harkey, D. (2001). *Guidelines and Recommendations to Accommodate Older Drivers and Pedestrians.a* (FHWA-RD-01-051). McLean, VA: FHWA, Research, Office of Safety R&D.
2. Isler, R.B., Parsonson, B.S., and Hansson, G.J. (1997) Age related effects of restricted head movements on the useful field of view of drivers. *Accident Analysis and Prevention, 29*(6), 793-801.
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4. Bahill, A.T., Adler, D., and Stark, L. (1975). Most naturally occurring human saccades have magnitudes of 15 degrees or less. *Investigative Ophthalmology, 14*(6), 468-469.
5. Gattis, J.L. and Low, S.T. (1998). Intersection Angle Geometry and the Driver's Field of View. *Transportation Research Record, 1612*, 10-16.

COUNTERMEASURES FOR IMPROVING ACCESSIBILITY FOR VISION-IMPAIRED PEDESTRIANS AT ROUNDABOUTS

Introduction

This guideline identifies *countermeasures for improving accessibility for vision-impaired pedestrians at roundabouts*. Title II of the Americans with Disabilities Act (ADA) requires that new and altered facilities constructed by, on behalf of, or for the use of state and local government entities be designed to be readily accessible to and usable by people with disabilities (28 CFR 35.151). Also, FHWA states that "a visually impaired pedestrian with good travel skills must be able to arrive at an unfamiliar intersection and cross it with pre-existing skills and without special, intersection-specific training" (*1*).

Roundabouts can be particularly challenging to navigate for vision-impaired pedestrians. In particular, vision-impaired pedestrians typically wait much longer to cross at roundabouts than sighted pedestrians, especially if traffic volume is high. One reason that sighted pedestrians have shorter wait times is that they can accept gaps that are initially too short but can be extended by driver yields and they can use eye gazes and manual gestures to communicate with drivers and get confirmation of driver yielding. Because vision-impaired pedestrians cannot communicate in this manner, they are forced to wait for what they deem to be sufficient gaps based on sound information. Another problem is that vision-impaired pedestrians rely heavily on sound cues to get a sense of what vehicles are doing. The continuous traffic flow within the circle can eliminate important sound cues about vehicle movements, in addition to masking sound cues from vehicles approaching the roundabout. Anecdotally, vision-impaired pedestrians typically state they would most likely avoid roundabouts if getting sufficient information about vehicle movements is too difficult.

Design Guidelines

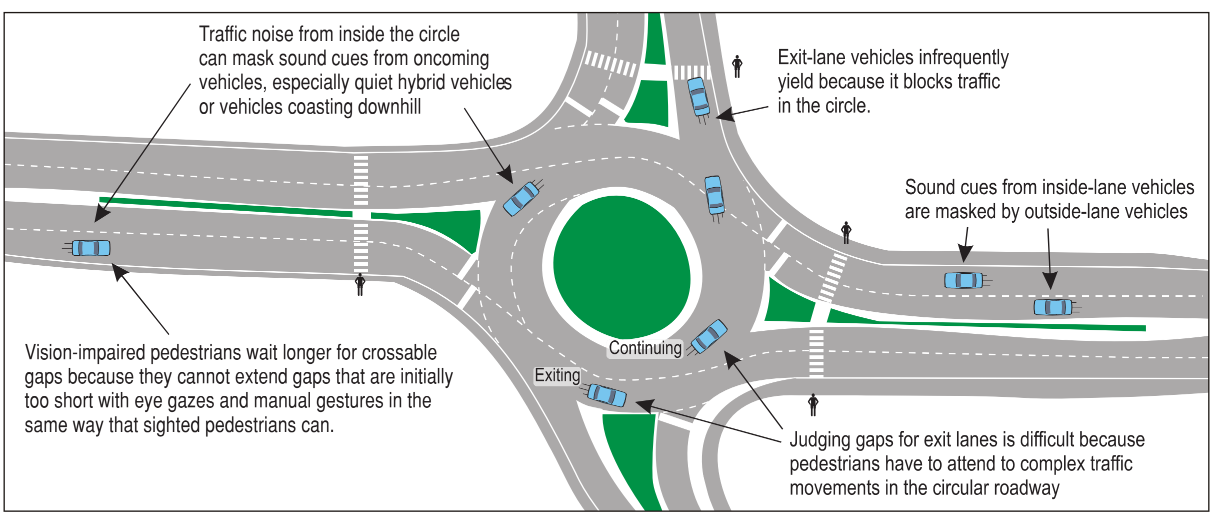
COUNTERMEASURES FOR IMPROVINGACCESSIBILITY FOR VISION-IMPAIRED PEDESTRIANS AT ROUNDABOUTS

Countermeasure	Applicable Situation	Effectiveness
Rumble/sound strips	Two-lane roundabouts	Poor
Rumble/sound strips	One-lane roundabouts	Unknown
Pedestrian-actualized traffic signals at midblock	One or two-lane roundabouts	Good*
Splitter island	One or two-lane roundabouts	Poor
Yield signs	One or two-lane roundabouts	Poor
Advanced vehicle detection technologies	One or two-lane roundabouts	Unknown

*Simulation results only. This countermeasure has not yet been field tested.

Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

The figure below illustrates some of the roundabout elements that cause navigation difficulties for vision-impaired pedestrians.



Discussion

Rumble/sound strips: One study (*2*) that looked at sound strips in two-lane roundabouts found that they increased the chance that a vision-impaired pedestrian would detect a stopping vehicle and also decreased the time needed to make the detection by more than 1 s. However, sound strips did not reduce false alarm rates, and the observed level of 13% false alarms makes this countermeasure unacceptable for deployment. One problem was that detecting a second stopping vehicle was particularly difficult if that vehicle was in the far lane because its sound was masked by the vehicle in the near lane. Participants in this study were not trained to use the sound cues provided by the pavement treatment, nor were they informed of the treatment before the debriefing. It is conceivable that with training, detection performance with the sound strips would have been better, and false alarms might have been reduced. However, the majority of vehicles stopped before reaching the sound strips and did not produce the intended sound, which may reduce the effectiveness of any training.

This same study found that detection of stopping vehicles was relatively high when only one lane of traffic had to be monitored at a time (80% to 90% correct), which suggests that a sound-strip pavement treatment may be effective in single-lane roundabouts. However, any benefits of sound strips would likely be diminished if drivers consistently stop before reaching the sound strips, as mentioned previously.

Pedestrian-actualized traffic signals at midblock: An analysis of pedestrian crossing treatments indicated that midblock signals appear to be a useful compromise between increasing safety/quality of service and reducing vehicle capacity (*3*). In particular, they appear to be effective in eliminating queues that back up into the intersection under most conditions. Midblock crosswalks also have the advantage of being farther away from the intersection traffic, which makes it easier for vision-impaired pedestrians to determine what is happening because there is less masking noise from traffic within the circle. Note, however, that these results are based on simulation research, and the results have not been studied empirically.

Splitter islands: These features pose special challenges to vision-impaired pedestrians and are still associated with gap judgment difficulties. For example, one study found that vision-impaired participants (1) were nearly 2.5 times *less* likely to make correct judgments than sighted participants, (2) took longer to detect crossable gaps, and (3) were more likely to miss crossable gaps altogether (*4*). However, these differences were only significant at higher volume roundabouts. Overall, judging gaps in the exit lane is particularly difficult for vision-impaired pedestrians because they have to attend to vehicles in the exit lane and the circulatory roadway. This difficulty is compounded by drivers infrequently yielding in the exit lanes, typically because such yielding tends to back up traffic in the roundabout.

Yield signs: Vision-impaired pedestrians typically failed to detect when drivers had yielded for them, which suggests that efforts to encourage driver yielding may be of limited use (*5*).

Design Issues

Because most vision-impaired and low-vision pedestrians rely primarily on sound cues to determine traffic conditions, quiet oncoming vehicles pose a potential hazard. In particular, hybrid vehicles operating in battery-powered mode and vehicles that coast downhill towards a roundabout can be difficult to hear above other traffic noise. In this case, providing sound strips or other measures that make these vehicles easier to hear may assist vision-impaired or low-vision pedestrians in detecting oncoming vehicles.

Cross References

Countermeasures for Improving Accessibility for Vision-Impaired Pedestrians at Signalized Intersections, 11-8

Key References

1. FHWA (2000). *Roundabouts: An Informational Guide* (Publication FHWA-RD-00-067). Washington, DC.
2. Inman, V.W., Davis, G.W., and Sauerburger, D. (2006). *Pedestrian Access to Roundabouts: Assessment of Motorists Yielding to Visually Impaired Pedestrians and Potential Treatments to Improve Access*. Washington DC: FHWA.
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4. Guth, D., Ashmead, D., Long, R., Wall, R., and Ponchillia, P. (2005). Blind and sighted pedestrians' judgments of gaps in traffic at roundabouts. *Human Factors, 47*(2), 314.
5. Ashmead, D.H., Guth, D., Wall, R.S, Long, R.G., and Ponchillia, P.E. (2005). Street crossing by sighted and blind pedestrians at a modern roundabout. *Journal of Transportation Engineering, 131*(11), 812-821.

CHAPTER 11

Signalized Intersections

ENGINEERING COUNTERMEASURES TO REDUCE RED LIGHT RUNNING

Introduction

Red light running refers to drivers' entering a signalized intersection when a red light is being presented (*1*). Several engineering countermeasures to reduce red light running have been proposed in McGee, Eccles, Clark, Prothe, and O'Connell (*1*) and Bonneson and Zimmerman (*2*). Some of these countermeasures reflect expert judgment, but most are supported by empirical research.

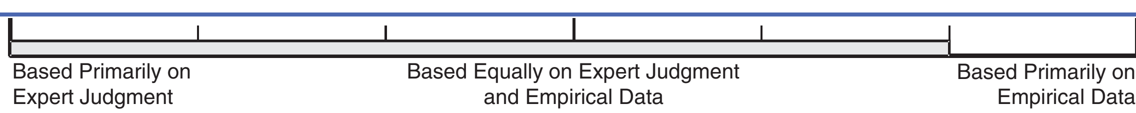
Importantly, Bonneson and Zimmerman (*2*) note the number of driver-, intersection-, vehicle-, and environment-related factors that are correlated with red light violation frequency and likelihood. These factors include traffic volume, cycle length, advance detection for green extension, speed, signal coordination, approach grade, yellow interval duration, proximity to other vehicles, presence of heavy vehicles, intersection width, and signal visibility.

Design Guidelines

The following engineering countermeasures address red light running at signalized intersections.

Countermeasure Type	Engineering Countermeasure
Traffic Characteristics, Operation, or Geometry	• Reduce approach speed by 5 mi/h • Reduce delay through retiming if volume-to-capacity (v/c) ratio > 0.70 • Reduce unnecessary delay through signal retiming • Improve signal coordination (goal is lower delays and longer cycle lengths) • Remove unneeded signals • Add capacity with additional lanes or turn bays
Signal Operation	• Increase signal cycle length by 10 s if v/c ratio < 0.60 • Provide green extension (advance detection) • Add protected-only left-turn phasing
Motorist Information	• Improve signal visibility via better signal head location • Improve signal visibility via additional signal head • Improve signal visibility by clearing sight lines to signal • Improve signal conspicuity by upgrading to 12-in. lenses • Improve signal conspicuity by using yellow LEDs • Improve signal conspicuity by using red LEDs • Improve signal conspicuity by using back plates • Improve signal conspicuity by using dual red indications • Add advance warning signs (can be with or without active flashers) • Add red light enforcement cameras

Source: Adapted from Bonneson and Zimmerman (*2*)



Discussion

Several driver-related factors and driver behaviors are relevant to red light running and countermeasure selection. Campbell, Smith, and Najm (*3*) report on a study that examined fatal crashes from 1999 and 2000 included in the Fatal Accident Reporting System (FARS) and found that, of the 9,951 vehicles involved at fatal signalized-intersection crashes, 20% failed to obey the traffic signal and 13% failed to yield the right-of-way; contributing factors included alcohol, speeding, and racing. Porter and Berry (*4*) note that in a survey that assessed red-light-running perceptions of 880 licensed drivers, the only factor that predicted recent red light running was age group—younger respondents were more likely to run red lights. In Retting and Williams (*5*), video data collected by an automated camera were analyzed to identify key characteristics of red light running. The authors found that, as a group, red light runners were younger, were less likely to be wearing seat belts, and had more convictions for moving violations. McGee et al. (*1*) summarizes the red-light-running problem, as well as a number of engineering countermeasures, and notes that driver-related factors associated with red light running include driver expectancies, driver knowledge of the intersection and the traffic signal (e.g., the yellow interval), and the driver's estimate of the consequences of not stopping (e.g., threat of a right-angle crash or a citation) versus stopping (e.g., threat of a rear-end crash or delays).

In Bonneson and Zimmerman (*2*), an integrative review of past analyses and research was conducted to identify engineering countermeasures having promise for reducing the number of red light violations at intersections and/or the number of crashes associated with red light violations. The engineering countermeasures presented on the opposing page have been adapted from Bonneson and Zimmerman (*2*), but are also presented in slightly different formats in McGee et al. (*1*) and Bonneson, Zimmerman, and Brewer (*6*).

Design Issues

McGee et al. (*1*) make an important distinction between intentional and unintentional red light running that can affect countermeasure selection and development. Specifically, McGee et al. (*1*) note that *intentional* red light runners are most affected by enforcement countermeasures (such as red light cameras) while *unintentional* red light runners are most affected by engineering countermeasures.

Red light cameras are frequently employed as enforcement countermeasures to reduce red light running. In Council, Persaud, Eccles, Lyon, and Griffith (*7*), an empirical Bayes before/after approach was used to determine effectiveness of red light cameras at 132 treatment sites. The authors report that red light cameras were associated with decreased right-angle crashes and increased rear-end crashes, with an aggregate crash cost-benefit associated with the use of red light cameras. Also, the presence of warning signs at both the city limit and the intersection was associated with a larger benefit than signs at just the intersection; high publicity was also associated with higher benefits. Caveats associated with the study were that other variables (driver, traffic volumes, temporal, environmental, signal) were either not included in the analyses (uncontrolled or confounded) or not associated with a large enough sample to detect an effect. Also, the analyses could not distinguish the effects of other improvements occurring at the same location as the red light cameras.

Cross References

Heuristics for Selecting the Yellow Timing Interval, 11-6

Key References

1. McGee, H., Eccles, K., Clark, J., Prothe, L., and O'Connell, C. (2003). *Making Intersections Safer: A Toolbox of Engineering Countermeasures to Reduce Red-Light Running*. Washington, DC: ITE.
2. Bonneson, J., and Zimmerman, K. (2004). *Red-Light-Running Handbook: An Engineer's Guide to Reducing Red-Light-Related Crashes*. College Station: Texas Transportation Institute.
3. Campbell, B.N., Smith, J.D., and Najm, W.G. (2004). *Analysis of Fatal Crashes Due to Signal and Stop Sign Violations* (DOT HS 809 779). Cambridge, MA: Volpe National Transportation Systems Center.
4. Porter, B.E., and Berry, T.D. (2001). A nationwide survey of self-reported red light running: Measuring prevalence, predictors, and perceived consequences. *Accident Analysis & Prevention, 22,* 735-741.
5. Retting, R.A., and Williams, A.F. (1996). Characteristics of red light violators: Results of a field investigation. *Journal of Safety Research, 27*(1), 9-15.
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7. Council, F.M., Persaud B., Eccles, K., Lyon, C., and Griffith, M.S. (2005). *Safety Evaluation of Red-Light Cameras*. (FHWA-HRT-05-048). McLean, VA: FHWA.

RESTRICTING RIGHT TURNS ON RED TO ADDRESS PEDESTRIAN SAFETY

Introduction

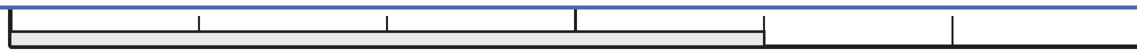
This guideline describes approaches for implementing restrictions on right turn on red (RTOR) movements with the objective of reducing conflicts between pedestrians and right-turning vehicles. The MUTCD (*1*) provides six situations where RTOR should be restricted, and three of these specifically address pedestrians: (1) where an exclusive pedestrian phase exists, (2) where significant pedestrian conflicts result from RTORs, and (3) where there is significant crossing activity by pedestrians who are children, are elderly, or have disabilities.

Typically, around 40% of drivers do not stop completely before making a RTOR (*2*). Of those drivers that do stop, many will stop beyond the marked stop line and block the pedestrian crosswalk while waiting to turn. This blocking of the crosswalk can impede pedestrian movements or cause pedestrians to walk outside of the marked crosswalk. Also, pedestrians may yield the right-of-way before entering the intersection and may not have time to clear the intersection before the signal changes. This is especially problematic for older pedestrians who take longer to cross.

Design Guidelines

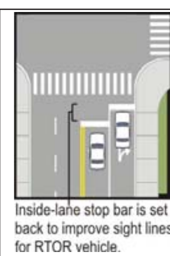
Restrictions on RTOR can be used to reduce conflicts between pedestrians and turning vehicles, and to increase the likelihood that drivers will stop before turning right at an intersection.

- The most effective method is to base turning restrictions on time of day (e.g., from 6:00 am to 6:00 pm).
- Basing restrictions on the presence of pedestrians at the intersection will also reduce conflicts; however, this approach appears to be significantly less effective than time-based restrictions.



Based Primarily on Expert Judgment | Based Equally on Expert Judgment and Empirical Data | Based Primarily on Empirical Data

The table below shows examples of different implementations for RTOR signage.

Countermeasure Example				
Effectiveness	Most effective	Effective with low to moderate volume of RTOR	Effective when sight distances are problematic	Effective

Countermeasure	Key Features	Preferred Application
Red Ball on NTOR Sign	More "eye catching"	This is an effective signing approach in most situations.
Larger 30″ x 36″ Size	More conspicuous	On the far side of a wide intersection.
"When Pedestrians are Present" Addition	Permits RTOR but requires drivers to yield to pedestrians	Sites with low to moderate volumes of RTOR and pedestrian volumes that are low or occur primarily during intermittent periods.
Offset Stop Bar	Provides improved sight distance to RTOR vehicle	Sites with two or more approach lanes, heavy truck or bus traffic, or unusual geometries.
Variable Blank-Out Signs	Lit only during times that RTOR is prohibited	When pedestrian protection is critical during certain time periods (e.g., in school zones) or during a signal cycle when a separate, opposing left-turn phase may conflict with an unsuspecting RTOR driver.
"Look for Turning Vehicles" Pavement Markings	Can make pedestrians more cautious	Sites with particular problems involving pedestrian crashes or conflicts with RTOR vehicles.

Discussion

With regard to conditional RTOR restrictions, restrictions based on certain times of day (time-restricted) and those based on the presence of pedestrians (pedestrian-restricted) increase drivers' stopping at the stop line (*3*). However, the time-restricted implementation appears to be more effective both when pedestrians are present and when they are not. Retting, Nitzburg, Farmer, and Knoblauch (*3*) found that the pedestrian-restricted implementation significantly reduced RTOR when pedestrians were present (by 11%), but they still occurred 57% of the time. In contrast, time-restricted implementation led to a much greater reduction (from 77% to 19%). Additionally, the time-restricted implementation significantly increased the number of drivers that stopped before making a RTOR, while the pedestrian-restricted implementation did not. There was also a difference in terms of pedestrian capacity. In particular, the time-restricted implementation significantly reduced the number of pedestrians that yielded to drivers, but the pedestrian-restricted implementation did not.

Time-restricted implementations can be based on when pedestrian–turning vehicle crashes are most likely to occur. In particular, Stutts, Hunter, and Pein (*4*) found that 80% of intersection crashes involving pedestrians and turning vehicles occur between 6:00 am and 6:00 pm.

Regarding the relative effectiveness of different signage options, Zeger and Cynecki (*5*) compared different approaches and found that the NO TURN ON RED (NTOR) sign with a red ball was more effective than the standard black and white NTOR sign. Also, NO TURN ON RED WHEN PEDESTRIANS ARE PRESENT signs were effective at sites with moderate to low volumes of RTOR vehicles, although the legend was found to be difficult to read when located adjacent to the signal or on the far side of the intersection. Lastly, the presence of an offset stop bar improved motorist compliance, reduced conflicts with cross-street traffic, and was recommended for use on multilane approaches under some conditions (see Zeger and Cynecki (*5*)).

Another issue to consider is the use of electronic signing, such as blank-out NTOR signs that are lit only during the times that turns are restricted. In Zeger and Cynecki (*5*), an electronic NTOR blank-out sign was slightly more effective, although considerably more costly, than traditional signs. Similarly, another study found that sites with variable message signs were effective in lowering incidence of motorists who illegally turned right on red. This study did not compare the effectiveness to traditional signs, so it is unclear if the benefits outweighed the additional costs of the variable message signs.

Design Issues

Several factors can diminish the effectiveness of RTOR restrictions on driver compliance (see Zeger and Zeger (*6*)):

- Confusing partial prohibitions (e.g., 7-9 am and 4-6 pm, except Sundays)
- Far-side or hidden NTOR signs
- Long cycle lengths
- Confusing multi-leg intersections
- NTOR that does not appear to be justified given the traffic conditions

Also, inconsistent placement of RTOR signs from intersection to intersection can reduce the effectiveness of the signs.

Cross References

Determining Intersection Sight Distance, 5-6
Sight Distance at Right-Skewed Intersections, 10-8

Key References

1. FHWA (2003). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.
2. ITE (1992). Driver behavior at right-turn-on-red locations. *ITE Journal, 62*(4), 18-20.
3. Retting, R.A., Nitzburg, M.S., Farmer, C.M., and Knoblauch, R.L. (2002). Field evaluation of two methods for restricting right turn on red to promote pedestrian safety. *ITE Journal, 72*(1), 32-36.
4. Stutts, J.C., Hunter, W.W., and Pein, W.E. (1996). Pedestrian-vehicle crash type: An update. *Transportation Research Record, 1538*, 68-74.
5. Zegeer, C.V., and Cynecki, M.J. (1986). Evaluation of countermeasures related to RTOR accidents that involve pedestrians. *Transportation Research Record, 1059*, 24-34.
6. Zegeer, C.V., and Zegeer, S.F. (1988). *NCHRP Synthesis of Highway Practice 139: Pedestrians and Traffic-Control Measures*. Washington, DC: Transportation Research Board.

HEURISTICS FOR SELECTING THE YELLOW TIMING INTERVAL

Introduction

The *yellow timing interval* refers to the duration of the yellow signal indication; the yellow timing interval is also referred to as the "yellow change interval" in a number of sources. The yellow signal warns oncoming traffic of an imminent change in the right-of-way assignment (*1*,*2*). Most traffic engineering sources (*1*,*2*,*3*) recommend a yellow change interval of 3 to 5 s duration. Increases to a given yellow timing interval are usually implemented in order to decrease instances of red light running. Van Winkle (*4*) notes that the many variables influencing the selection of yellow timing intervals include approach speed, intersection width, vehicle length, vehicle deceleration level, visibility of traffic signals, response time of the driver, degree of enforcement, specific laws, and motorist attitudes; this source also recommends using a consistent interval to eliminate driver uncertainty as a variable.

Design Guidelines

Pline (*1*) and ITE Technical Council Committee 4TF-1 (*5*) indicate that the following formula can be used to calculate the yellow timing interval time plus the red clearance interval time.

Metric Values [English Values]

$$CP = t + \frac{V}{2a + 2Gg} + \frac{W + L}{V}$$

Metric:
- a = deceleration, m/s^2 (typically 3.1 m/s^2)
- G = gravity @ 9.8

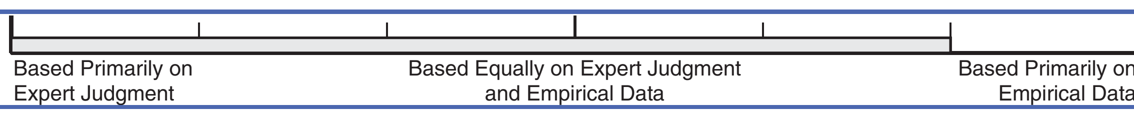
English:
- a = deceleration, ft/s^2 (typically 10 ft/s^2)
- G = gravity @ 32.2

Where:
- CP = non-dilemma change period (Change + Clearance Intervals)
- t = perception-reaction time (nominally 1 s)
- V = approach speed, m/s [ft/s]
- g = percent grade (positive for upgrade, negative for downgrade)
- a = deceleration, m/s^2 (typical 3.1 m/s^2) [ft/s^2 (typical 10 ft/s^2)]
- W = width of intersection, curb to curb, m [ft]
- L = length of vehicle, (typical 6 m) [ft (typical 20 ft)]

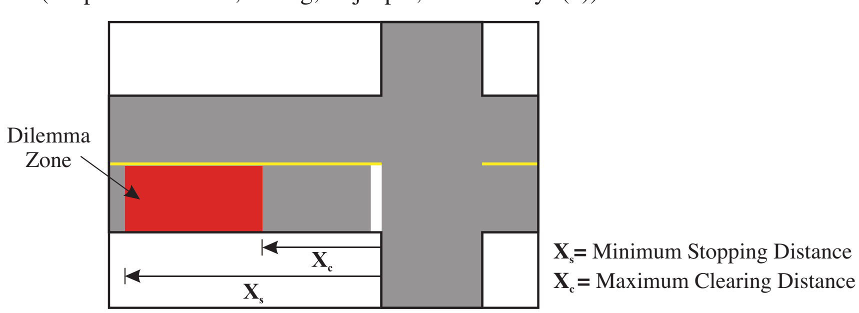
From Pline (*1*):

- Yellow timing intervals should generally have a duration of 3 to 5 s. If more than 5 s is required, a red clearance interval is used.
- Because a longer interval may encourage drivers to use the yellow as a part of the green interval, a maximum of about 5 s for the yellow timing interval is generally used.
- When the calculation for the yellow timing interval yields a time greater than 5 s, a red clearance interval generally provides the additional time.
- Given the many variables included in the formula above (estimates for reaction time, vehicle deceleration, grades, and intersection clearing time), engineering judgment should be used to apply the results of these calculations toward determining the yellow change interval.

FHWA (*2*) notes that the yellow timing interval "may be followed by an optional red clearance interval to provide additional time before conflicting traffic movements, including pedestrians, are released"; it further notes that this all-red interval should not exceed 6 s.



The figure below depicts the dilemma zone when a driver approaching a signalized intersection is faced with a green light that changes to yellow (adapted from Pant, Cheng, Rajaopal, and Kashayi (*8*)).



Discussion

Driver behaviors relevant to the selection of a yellow timing interval have been studied by the transportation research community for many years. Tijerina, Chovan, Pierowicz, and Hendricks (*6*) note that crash data for signalized intersections show that the decision to proceed through a yellow signal likely represents a source of problems for many drivers.In particular, the most common contributing factors include deliberately running the signal (40%), either because drivers failed to obey the signal (23.1%) or tried to beat the signal (16.2%). The next most common contributing factor was driver inattention (36.4%). A critical aspect of driver behavior related to the yellow timing interval is associated with the "dilemma zone." When a driver sees a green signal changing to yellow, a dilemma zone is created. The dilemma zone represents the portion of the roadway between (1) the clearing distance to the intersection (the distance the vehicle travels between the time the signal changes to yellow to the time the signal changes to red) and (2) the stopping distance (the distance traveled by the vehicle between the time the signal changes to yellow to the time when the vehicle actually stops) when the stopping distance is greater than the clearing distance. The dilemma zone is therefore not a fixed area. While in the dilemma zone, the driver must assess the situation and then decide whether to stop or proceed through the intersection based on that assessment.

A recent task analysis of driver behavior while traveling straight through an intersection on a yellow signal (*7*) confirms that the decision to stop or not is a complex one. As noted in Richard, Campbell, and Brown (*7*), there are two reasons drivers run the signal (and risk a right-angle crash) when the appropriate action would be to stop: (1) they correctly assess the situation as unsafe and then make a bad decision to go anyway, or (2) they incorrectly assess the situation as safe (perhaps because the driver missed relevant information) and make the logical—but incorrect—decision to proceed. The latter case is similar to driver inattention, whereby drivers also fail to adequately perceive and process the necessary situational information. Overall, it is clear that dilemma zone situations provide limited options for drivers not only because they have an extremely limited amount of time to perform several tasks, but also because they are limited in the types of actions they can safely or legally take.

Pant et al. (*8*) carried out a study to test and implement a dilemma zone protection technique (placement of detectors leading up to the intersection and the use of a green extension of 1 to 5 s) at three high-speed intersections in Ohio. The authors report that the use of detectors, combined with a 3-s extension, can provide drivers with some dilemma zone protection. They also note that differences among intersections with respect to vehicle speeds, operational characteristics, and geometries suggest that specific solutions are unique to individual intersections.

Design Issues

The possibility of long-term driver adaptation to longer yellow timing intervals has not been extensively studied. Specifically, the driver behavior and crash rates associated with changes in the yellow timing interval seen in many of the field studies in this area may reflect only temporary effects that will recede once drivers acclimate to the longer yellow.

Cross References

Engineering Countermeasures to Reduce Red Light Running, 11-2

Key References

1. Pline, J.L. (Ed.). (2001). *Traffic Control Devices Handbook*. Washington, DC: ITE.
2. FHWA (2003). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.
3. Pline, J.L. (Ed.). (1999). *Traffic Engineering Handbook, Fifth Edition*. Washington, DC: ITE.
4. Van Winkle, S.N. (1999). Clearance interval timing—a viewpoint. *Transportation Frontiers for the Next Millennium: 69th Annual Meeting of the Institute of Transportation Engineers* (p. 3). Washington, DC: ITE.
5. ITE Technical Council Committee 4TF-1. (1994). *Determining Vehicle Signal Change and Clearance Intervals (IR-073)*. Washington, DC: ITE.
6. Tijerina, L., Chovan, J., Pierowicz, J., and Hendricks, D. (1994). *Examination of Signalized Intersection, Straight Crossing Path Crashes, and Potential IVHS Countermeasures* (DOT HS 808 143). Washington, DC: National Highway Traffic Safety Administration.
7. Richard, C.M., Campbell, J.L., and Brown, J.L. (2006). *Task Analysis of Intersection Driving Scenarios: Information Processing Bottlenecks* (FHWA-HRT-06-033). Washington, DC: FHWA.
8. Pant, P.D., Cheng, Y., Rajaopal, A., and Kashayi, N. (2005). *Field Testing and Implementation of Dilemma Zone Protection and Signal Coordination at Closely-Spaced High-Speed Intersections*. Columbus, OH: Department of Transportation.

COUNTERMEASURES FOR IMPROVING ACCESSIBILITY FOR VISION-IMPAIRED PEDESTRIANS AT SIGNALIZED INTERSECTIONS

Introduction

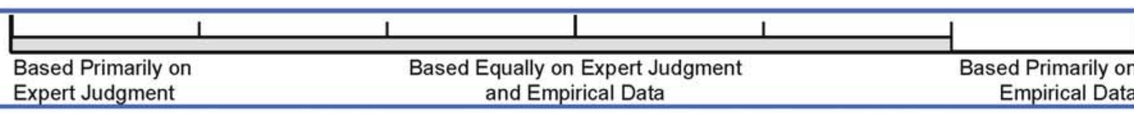
This guideline identifies accessible pedestrian signals (APSs) and curb treatment recommendations for improving accessibility for vision-impaired pedestrians at signalized intersections. Title II of ADA requires that new and altered facilities constructed by, on behalf of, or for the use of state and local government entities be designed to be readily accessible to and usable by people with disabilities (28 CFR 35.151). Unfamiliar signalized intersections can pose several challenges that reduce accessibility and safety for vision-impaired or low-vision pedestrians who use signalized intersections while traveling on their own (*1*).

Design Guidelines

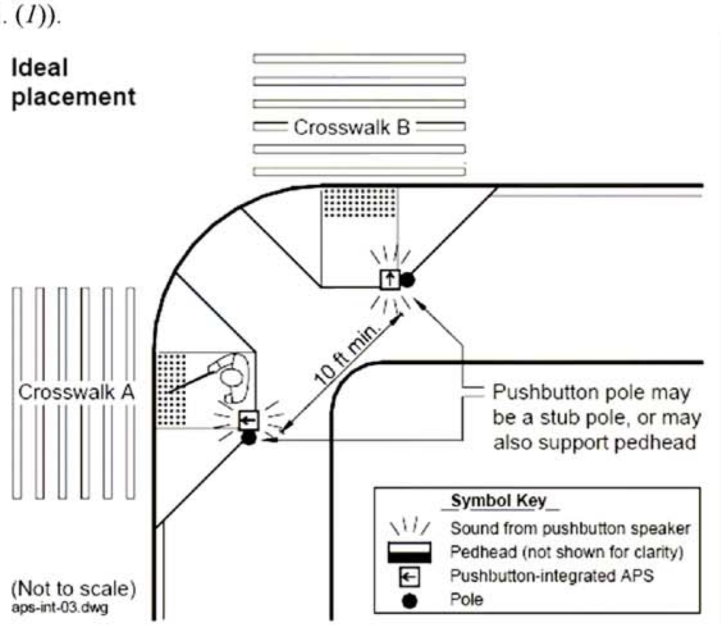
COUNTERMEASURES FOR IMPROVING ACCESSIBILITY AT SIGNALIZED INTERSECTIONS

Recommendation	Rationale
Avoid using large-radius corners and curb ramps aligned at various angles.	These corners and ramps make it more difficult for vision-impaired pedestrians to align themselves with the crosswalk.
Use domed curb-ramp surfaces instead of rough aggregate surfaces.	A majority of vision-impaired pedestrians fail to detect rough aggregate surfaces.
Lengthen the pedestrian walk interval by 5 to 8 s.	Vision-impaired pedestrians require more time to prepare for crossing and tend to start crossing later.
Use an APS implementation consistent with features in figure below and with recommendations from Barlow, Bentzen, and Tabor (*1*).	Poorly implemented APSs can lengthen the time that vision-impaired pedestrians require for crossings.

Note: Chapter 6 of Barlow et al. (*1*) has additional recommendations regarding walk indications (including location, tones, speech messages, vibration surfaces, volume, and audible beaconing) and other APS features (including pushbutton locator tone, tactile arrow, pushbutton information message, automatic volume adjustment, alert tone, actuation indicator, tactile map, Braille and raised-print information, extended button press, passive pedestrian detection, and clearance interval tones).



The figure below shows the ideal placement of pushbutton integrated APS and recommended positioning of curb ramps (from Barlow et al. (*1*)).



Discussion

Curb ramps: Aligning themselves with the crosswalk and staying within it are some of the biggest challenges that vision-impaired pedestrians face at intersections. One study found that only 66% to 75% of pedestrians started within the crosswalk, started from an aligned position, traveled within the crosswalk, and ended within the crosswalk (*2*). Two factors that contribute to these problems are large-radius corners that eliminate important cues for alignment, and curb ramps that do not line up with the crosswalk, which make finding the crosswalk more difficult for vision-impaired pedestrians (*3*). Factors that help vision-impaired pedestrians detect the crosswalk location include a ramp slope that has a steep angle, an abrupt rate of change in the slope between the approach to each curb and the ramp itself, and curb ramps aligned with the crosswalk (*4*).

O'Leary, Lockwood, and Taylor (*5*) found that domed surfaces were far more detectable than rough aggregate surfaces and that a majority of the totally vision-impaired participants failed to detect either of two exposed rough aggregate surfaces.

Signal timing: Vision-impaired pedestrians can cross at the same speed as other pedestrians (4 ft/s), but they require additional time before crossing to determine that it is safe to cross (by listening to the near-side parallel vehicle surge). This additional time can result in pedestrians leaving the curb during the clearance interval after the initial "walk" interval has passed. Bentzen, Barlow, and Bond (*2*) found that mean starting delay ranged from 5 to 8 s and resulted in 26.2% of all crossings being completed *after* the onset of perpendicular traffic.

APS: As indicated in the guideline, recommended characteristics for APSs (e.g., location, tones, speech messages) and associated pushbuttons (e.g., locator tone, tactile arrow, information message) are covered in detail in Barlow et al. (*1*). These recommendations address important difficulties that vision-impaired pedestrians encounter with APSs and pushbuttons. In particular, common problems with APSs include (1) identifying which crosswalk had the signal, (2) hearing a signal that is too quiet, (3) remembering which sound is for which direction, and (4) finding the APS (*6*). Additionally, common problems with pushbuttons include (1) not being able to determine if a pushbutton is present, (2) locating the pushbutton, (3) identifying which crosswalk is actuated by the pushbutton, and (4) having insufficient time to prepare for crossing because pushbuttons are located too far from the crosswalk (*6*).

Design Issues

The MUTCD (*7*) states that APS implementation should be based on engineering studies that consider the following factors: (1) potential demand for accessible pedestrian signals; (2) a request for accessible pedestrian signals; (3) traffic volumes during times when pedestrians might be present, including periods of low traffic volumes or high turn-on-red volumes; (4) the complexity of traffic signal phasing; and (5) the complexity of intersection geometry.

Additional guidance about locations that may require APSs are presented in Barlow et al. (*1*) and include the following:

- Intersections with vehicular and/or pedestrian actuation
- Very wide crossings
- Non-rectangular or skewed crossings
- T-shaped intersections
- High volumes of turning vehicles
- Major streets at intersections with low-traffic minor streets (an APS may be needed for crossing the major street)
- Split phase signal timing
- Exclusive pedestrian phasing, especially where right-turn-on-red is permitted
- A leading pedestrian interval

Cross References

Countermeasures for Improving Accessibility for Vision-Impaired Pedestrians at Roundabouts, 10-10

Key References

1. Barlow, J.M., Bentzen, B.L., and Tabor, L.S. (2003). *Accessible Pedestrian Signals: Synthesis and Guide to Best Practices*. Final Report, NCHRP Project 3-62. Berlin, MA: Accessible Design for the Blind. http://www.walkinginfo.org/aps
2. Bentzen, B.L., Barlow, J.M., and Bond, T. (2004). Challenges of unfamiliar signalized intersections for pedestrians who are blind: Research on safety. *Transportation Research Record, 1878*, 51-57.
3. Barlow, J.M. (2004). Orientation and alignment for street crossing: pedestrians who are blind or visually impaired. *Curb Ramp and Intersection Wayfinding Workshop*. Washington, DC: ITE.
4. Bentzen, B.L., and Barlow, J.M. (1995). Impact of curb ramps on the safety of persons who are blind. *Journal of Visual Impairment & Blindness*, 89(4), 319-328.
5. O'Leary, A.A., Lockwood, P.B., and Taylor, R.V. (1996). Evaluation of detectable warning surfaces for sidewalk curb ramps. *Transportation Research Record, 1538*, 47-53.
6. Bentzen, B.L., Barlow, J.M., and Franck, L. (2000). Addressing barriers to blind pedestrians at signalized intersections. *ITE Journal, 70*(9), 32-35.
7. FHWA (2003). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.

CHAPTER 12

Interchanges

Forthcoming

CHAPTER 13

Construction and Work Zones

PROCEDURES TO ENSURE PROPER ARROW PANEL VISIBILITY

Introduction

Arrow panel visibility depends on a number of factors, including the capability of the lamps in the panel, the type of roadway, the physical location of the panel, the panel's relation to horizontal and vertical curves, ambient light, and weather. Procedures to ensure arrow panel visibility should include specifications for the arrow panel as well as field procedures to check in-service arrow panels.

Design Guidelines

ARROW PANEL SPECIFICATIONS
RECOMMENDED PHOTOMETRIC REQUIREMENTS

Time of Day	Speed (mi/h)	Minimum On-Axis		Minimum Off-Axis		Maximum On-Axis
		cd/lamp	cd/panel[a]	cd/lamp	cd/panel[a]	cd/panel[a]
Day	≥ 45	500	4000	100	800	NA
Night	≥ 45	150	1200	30	240	5500

[a] Intensity requirements for the entire panel when displaying a left or right flashing arrow (10 lamps illuminated)
Source: Wooldridge, Finley, Denholm, Mace, and Patrick (*1*).

Note: cd = Candela: the SI base unit of luminous intensity

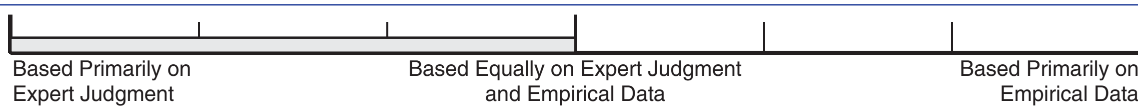
Angularity Requirements
- Minimum angularity permitted for a Type C (high-speed and high-volume roads) arrow panel should be +/– 4° in horizontal plane (8° beam width) and +/– 3° in the vertical plane (6° beam width).

Field Procedures
- Use of luminance to intensity measurements.
- Arrow should be oriented to be recognizable from 1500 ft even in curves (see figure below).

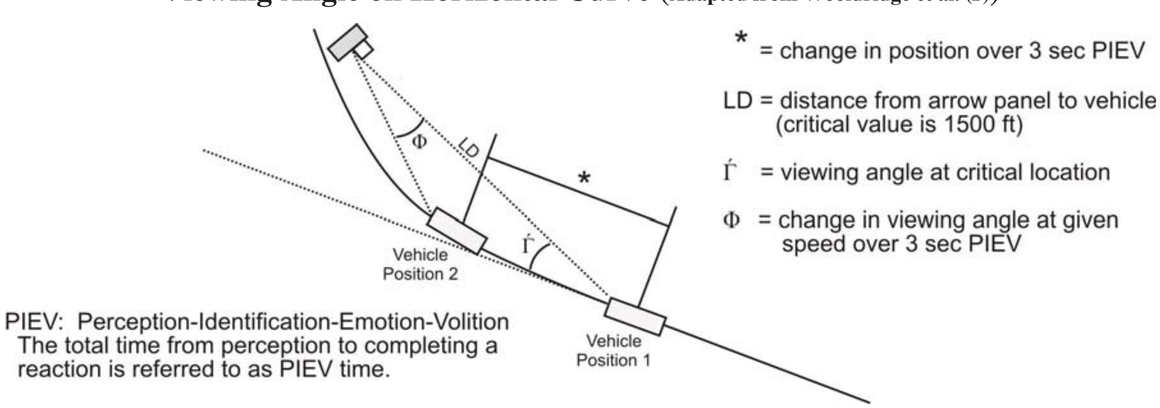
Effect of Arrow Panels
- In lane closures, arrow panels produced almost-ideal lane changing patterns.
- In traffic diversions, arrow panels produced some unnecessary lane changing.
- Arrow panels had little effect on traffic operations in moving shoulder closures on freeways.

Panel Luminous Intensity
- Field test resulted in recommendations for daytime of 4000 cd/panel as the minimum on-axis intensity and 800 cd/panel as the minimum off-axis intensity and a recommendation for nighttime of 5500 cd/panel as the maximum on-axis intensity.

Flash Rate
- 25 to 40 flashes/min.



Viewing Angle on Horizontal Curve (**Adapted from Wooldridge et al. (*1*)**)



Discussion

Human factors studies conducted as part of this research are discussed in detail in Knapp and Pain (*2*).

In Graham, Migletz, and Glennon (*3*), the effect of arrow panels was judged in three situations: (1) when a lane is closed; (2) in diversions where traffic is shifted, but lanes are not closed; and (3) in shoulder work zones. The following findings were reported:

- In lane closures, the presence of an arrow panel produced lane changing patterns that are closer to ideal. In other words, the arrow panel encouraged drivers to leave the closed lane sooner and, consequently, fewer lane changes occurred close to the lane closure taper.
- In traffic diversions, arrow panels produced some unnecessary lane changing; however, the number of these lane changes was small, particularity at night and for truck traffic. In traffic splits, the arrow panel caused vehicles to either remain in or move to the right lane, and decreased conflicts involving vehicles changing lanes near the split.
- Arrow panels had little effect on traffic operations in moving shoulder closures on freeways. Conflicts due to slow-moving vehicles were greater when the caution-bar mode was used.
- No differences were detected in the effect of various arrow panel modes such as the flashing arrow or sequential chevron (*4*).

Wooldridge et al. (*1*) made the following recommendations based on a field test conducted to examine requirements for panel luminance intensity:

- Minimum nighttime on-axis intensity of 150 cd/lamp luminance
- Minimum nighttime off-axis intensity of 30 cd/lamp luminance
- Minimum daytime on-axis intensity of 500 cd/lamp luminance
- Minimum daytime off-axis intensity of 100 cd/lamp luminance
- If arrow panels are located on curves, orient them to be seen by a vehicle 1500 ft upstream.
- Realign the arrow panel to be perpendicular to the driver's line of sight at the distance desired for observation
- Minimum daytime on-axis intensity of 4000 cd/panel, minimum daytime off-axis intensity of 800 cd/panel, and maximum nighttime on-axis intensity of 5500 cd/panel

Design Issues

Field conditions such as fog or a high level of ambient light (advertising signs) might impact the visibility of the arrow panel in the field.

Mace, Finkle, and Pennak (*5*) note that the arrow panel should flash at a rate of 25 to 40 flashes per minute.

Cross References

Caution Mode Configuration for Arrow Panels, 13-4
Determining When to Use Decision Sight Distance, 5-8

Key References

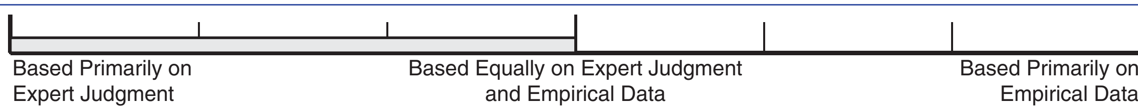
1. Wooldridge, M.D., Finley, M., Denholm, J., Mace, D., and Patrick, B. (2001). *Photometric Requirements for Arrow Panels* (TX-02/4940-1). College Station: Texas A&M University.
2. Knapp, B., and Pain, R.F. (1979). Human factors considerations in arrow-board design and operation. *Transportation Research Record 703*, 1-8.
3. Graham, J.L., Migletz, J., and Glennon, J.C. (1978). *Guidelines for the Applications of Arrow Boards in Work Zones* (FHWA-RD-79-58). Washington, DC: FHWA.
4. FHWA (2003). *Manual on Uniform Traffic Control Devices(MUTCD)*. Washington, DC.
5. Mace, D., Finkle, M., and Pennack, S. (2001). *NCHRP Research Results Digest 259: Guidelines for the Effective Use and Procurement of Advanced Warning Arrow Panels*. Washington, DC: Transportation Research Board.

CAUTION MODE CONFIGURATION FOR ARROW PANELS

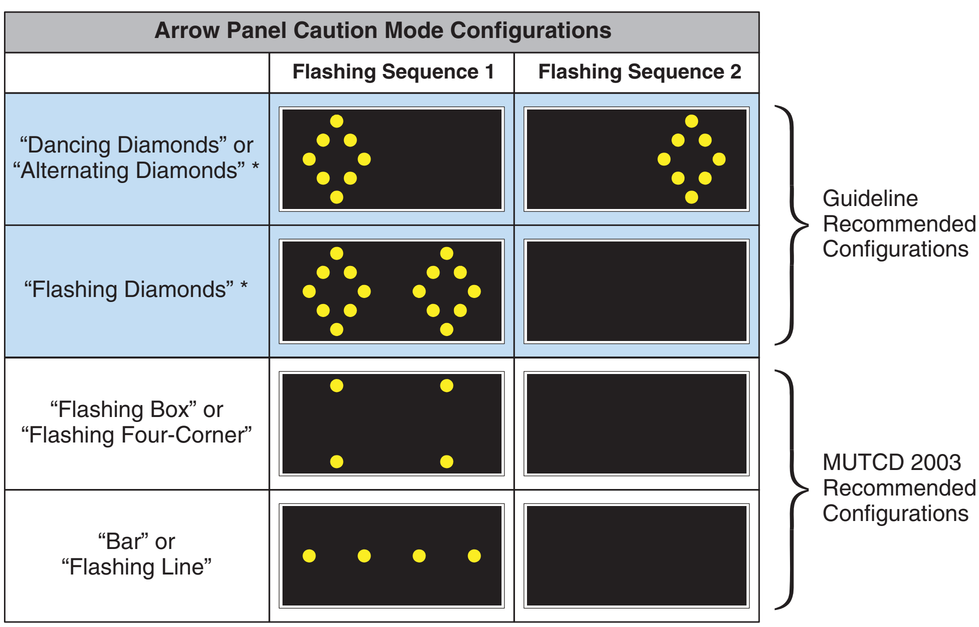
Introduction

This guideline provides recommendations for how to use the arrow panel *Caution Mode* configuration during temporary traffic control (*1*). The Caution Mode configuration is arrow panel mode C and provides flashing non-directional information. The purpose of the Caution Mode configuration is to increase safety near highway work zones by providing early warning information to drivers indicating that caution is required while approaching and traveling through the work zone. Note that these displays are only intended to alert drivers and to call attention to the appropriate signs, channelization devices, or other temporary traffic control devices that provide the actual information that drivers must use to safely navigate the work zone.

Design Guidelines	
Caution Mode Usage	The MUTCD (*1*) states that the Caution Mode configuration should be used for the following situations: • Shoulder work • Blocking of the shoulder • Roadside work near the shoulder • Temporary closing of one lane on a two-lane, two-way roadway
Caution Mode Display	Although the MUTCD states that Flashing Box or Flashing Line displays should be used, Alternating or Flashing Diamond displays are recommended over other displays because they are more attention getting and less confusing. Flash rates of 25 to 40 flashes/min should be used.



The figure below provides examples of different types of Cautionary Mode configurations for arrow panels (adapted from Saito and Turley (*2*).



* Use of this configuration may require the formal creation of an experimental project with FHWA.

Discussion

Caution Mode usage: The Caution Mode configuration should be used when directional information is not warranted (e.g., no merge is necessary), such as for shoulder work, blocking the shoulder, or roadside work near the shoulder (*1*). Some state DOTs also use the Caution Mode for slow-moving operations, such as street sweeping and striping (*3*). Note that the MUTCD (*1*) states that the Caution Mode is the *only* permissible usage of arrow panels when one lane must be closed on a two-lane, two-way street. Similarly, the Caution Mode should be used only if no lane change or merge is required. Consistent use of the Caution Mode in this situation helps drivers maintain a clear idea about how they should respond when seeing this display (and the same holds for arrow displays). If lane changes or merging is required on multi-lane roadways, then the arrow or chevron arrow-panel display must be used (*1*).

Caution Mode display: The diamond-based Caution Mode displays recommended in this guideline are different from the MUTCD recommended displays, and they are not MUTCD-compliant. However, the primary reasons for recommending these diamond displays is that they appear to lead to no worse performance than MUTCD-compliant displays, while at the same time providing a display that drivers find easier to see, more attention getting, and less confusing.

Two recent studies have compared the effects of diamond-based displays versus Flashing Box and Flashing Line displays on driver performance (*2,3*). Overall, Alternating Diamond displays lead to driver behavior that is not really different from that engendered by other display types in terms of lane migration, potential conflicts, and driver slowing (although diamond displays lead to a slightly greater degree of slowing with a statistically significant 2 mi/h reduction in mean speeds). These studies have also found important differences in driver opinions regarding the different display types (*2,3*). In particular, drivers rated the Alternating Diamond displays as easier to see, more attention getting, and less confusing than the other displays (*3*). Also, a Flashing Box display rated very poor in terms of prompting safe driving and was also rated as being much more likely to be ignored relative to Flashing and Alternating Diamond displays (*2*).

These findings are consistent with earlier research and opinions among highway researchers and administrators. For example, Knapp and Pain (*4*) found that more than 50% of drivers misinterpreted the meaning of Flashing Line and Flashing Box displays. Similarly, there is some broader concern that the Flashing Line display can be interpreted as a malfunctioning flashing arrow, resulting in unnecessary lane changes (*5*).

Finally, from a human factors perspective, the diamond displays should also be more salient and attention getting to drivers in potentially cluttered work zone environments because they are associated with a larger change of luminance (more lamps are illuminated).

Design Issues

There are no data currently available to suggest that either the flashing version or alternating version of the diamond displays is superior.

Flashing rate should be 25 to 40 flashes per minute.

Cross References

Procedures to Ensure Proper Arrow Panel Visibility, 13-2

Key References

1. FHWA (2003). *Manual on Uniform Traffic Control Devices(MUTCD)*. Washington, DC.
2. Saito, M., and Turley, B.M. (2002). *Dancing Diamonds in Highway Work Zones: An Evaluation of Arrow-Panel Caution Displays* (UT-02.13, Final Report). Provo, UT: Brigham Young University.
3. Griffith, A., and Lynde, M. (2001). *Evaluation of Arrow Panel Displays for Temporary Work Zones; Final Report* (FHWA-OR-RD-02-02). Salem: Oregon Department of Transportation.
4. Knapp, B., and Pain, R.F. (1979). Human factors considerations in arrow-board design and operation. *Transportation Research Record 703*, 1-8.
5. Noel, E.C., Sabra, Z.A., and Dudek, C.L. (1989). *Work Zone Traffic Management Synthesis: Selection and Application of Flashing Arrow Panels* (FHWA-TS-89-034). McLean, VA: FHWA. http://www.fhwa.dot.gov/tfhrc/safety/pubs/89034/89034.pdf

CHANGEABLE MESSAGE SIGNS

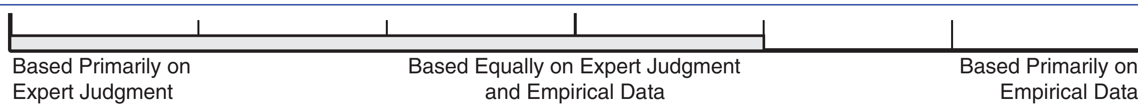
Introduction

Changeable message signs (CMSs) are electronic, reconfigurable signs placed above or near the roadway. They are used to inform motorists of specific conditions or situations. CMSs must communicate messages clearly in a brief period of time. Improper CMS usage defeats its credibility and can cause motorist confusion. Display messages ideally should be limited to a maximum of two phases. Many three-phase messages can be reduced to two or one phase by eliminating unnecessary wording. Other issues to avoid include splitting information across phases, using multiple formats of calendar dates, and displaying out-of-date information.

Design Guidelines

Fundamental human factors, identified mostly in Dudek (*1*), govern the use of CMSs. Some factors that should be considered follow.

Message Length and Format	Words should be simple and messages standardized. Abbreviations should be used only when easily understood.
The "Units" Rule	For road speeds > 35 mi/h, use a maximum of four units (one unit = one answer to one question). For examples, see revised message below. For road speeds ≤ 35 mi/h use a maximum of five units.
Device Consideration	CMSs should be placed so that approaching drivers see them 1500 ft or more upstream, and they are not overpowered by competing road or advertising signs or conditions.
Maximum Number of Words	Eight for 55 mi/h roads and seven for 65 mi/h roads.



Examples of how to revise a message to reduce reading time.

Message Element	Original Message	Revised Message
	Incident on Same Freeway as CMS Location	
Incident Descriptor	MAJOR ACCIDENT	FREEWAY BLOCKED (Unit 1)
Location	PAST I-80	PAST I-80 (Unit 2)
Lanes Affected	ALL LANES BLOCKED	
	Incident on Freeway Other than CMS Location	
Incident Descriptor	MAJOR ACCIDENT	I-76 WEST BLOCKED
Location	ON I-76 WEST AT WALT WHITMAN BRIDGE	AT WALT WHITMAN BRIDGE
Lanes Affected	ALL LANES BLOCKED	

Discussion

Message length and format: Because of the limited space on CMSs, suggestions for use are as follows:

- Messages should abbreviate the month in conjunction with the date.
- When future work will span days, the month should be noted only once in the message.

Other factors to consider include the following:

- Attempts to present day, date, and time information about upcoming roadwork appear to approach the limit of driver information processing.
- Regardless of the format used, only about two-thirds to three-quarters of the drivers viewing the portable changeable message sign (PCMS) will be able to correctly tell whether the work activity will affect their trip (*2*).

The "Units" rule: One unit of information equals one answer for one question. Research and operational experience indicate that no more than four units of information should be in a CMS when the traffic operating speeds are 35 mi/h or more. No more than five units of information should be displayed when the operating speeds are less than 35 mi/h. In addition, no more than three units of information should be displayed on a single message frame (*1*).

Because motorists can process only a limited amount of information at a given time, legibility and distance must be kept in mind. Based on the known legibility distance of CMSs, the calculated maximum message length that can be read by motorists is eight words for a traveling speed of 55 mi/h and seven words for a speed of 65 mi/h. A driver traveling at 60 mi/h is moving at 88 ft/s and can see a CMS for only 7.4 s at that speed (generally a CMS is legible for 650 ft) (*1*).

Device consideration: ITE's proposed equipment standard states that each PCMS unit shall be self-contained and consist of a message board, controller, power supply, electric cable, and adjustable height structural support system. The PCMS shall be suitable for either moving on a truck or two-wheeled trailer (*3*). The MUTCD (*4*) states that PCMSs mounted on trailers or large trucks should have a minimum letter height of 450 mm (18 in.). CMSs mounted on service patrol trucks should have a minimum height of 250 mm (10 in.). Each character should consist of a matrix at least five pixels wide and seven pixels high. The color of the elements should be yellow or orange on a black background. In addition, research suggests the following guidelines for CMS use:

- Device format should permit maximum amount of information display at a glance.
- CMS devices should be located 0.75 mi in advance of closure.
- CMS devices are to be considered supplemental to currently applied standard traffic control device schemes.
- CMS devices are not to be considered as an alternative to the arrow panel (*5*).

Design Issues

None.

Cross References

Sign Legibility, 13-8

Key References

1. Dudek, C. (2002). Guidelines for changeable message sign messages. Presentation at theTMC Pooled-Fund Study Annual Meeting, Arlington, VA. Retrieved on July 21, 2006, from http://tmcpfs.ops.fhwa.dot.gov/meetings/mtg_detail.cfm?id=10
2. Ullman, G.L., Ullman, B.R, Dudek, C.L, Williams, A., and Pesti, G. (2005). *Advanced Notification Messages and Use of Sequential Portable Changeable Message Signs in Work Zones*. College Station, Texas A&M University.
3. ITE (1988). Portable bulb-type changeable message signs for highway work zones: Proposed equipment standard. *ITE Journal, 58*(4), 17-20.
4. FHWA (2003). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.
5. Hanscom, F.R. (1982). Effectiveness of Changeable Message Signing at Freeway Construction Site Lane Closures. *Transportation Research Record, 844*, 35-41.

SIGN LEGIBILITY

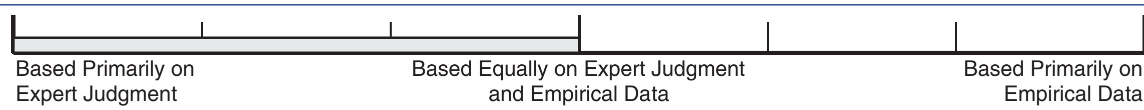
Introduction

Sign legibility refers to specific design characteristics of work zone signs that contribute to drivers' ability to perceive and understand the sign's message. A number of factors determine the legibility of work zone signs including retroreflectivity (sheeting type), color, letter font, and location of sign (roadside or overhead). The legibility index of various sign sheeting can be used to ensure designs that can accommodate all drivers regardless of age and light conditions. Prismatic sheeting ensures greater retroreflectivity of work zone signs and the addition of fluorescent colors improves the sign conspicuity in daytime low-light conditions such as dusk, dawn, or fog conditions.

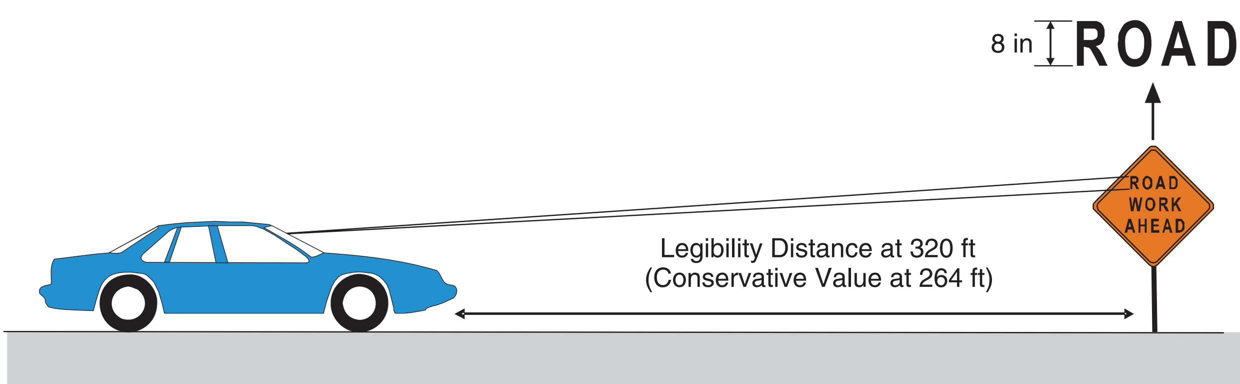
Design Guidelines

Studies conducted in Texas (*1*) have the following findings:

Color	Overall, yellow and white backgrounds on signs provide the greatest legibility distances followed by green and then orange backgrounds. The MUTCD requires the use of an orange background and black letters in work zone signs (*2*).
Retroreflectivity (Sheeting Type)	Fluorescent microprismatic sheeting with orange background provide for greater legibility distance than high-intensity sheeting.
Letter Height	A maximum legibility index of 40 ft of distance/in. of letter height should be used; a more conservative value is 33 ft/in, which is especially good for older drivers.



The figure below describes legibility distance for work zone signs.



Discussion

Retroreflectivity: A report by the Virginia Transportation Council has specified that for a prismatic lens retroreflective sheeting material, the specification should include values for the material's orientation and rotation angles, in addition to its entrance and observation angles (*3*). For high-speed (usually greater than 50 mi/h) highways, anywhere a critical vehicle maneuver is necessary, and in areas of high to medium visual complexity, higher values of sign luminance are required for safety (*4*). Another report finds that for existing traffic control devices, the beneficial effects of upgrading the type of sheeting used on barrels, barricades, and vertical panels were demonstrated by increased detection and recognition distances. However, the super-engineering grade offered the most cost-effective and balanced solution for upgrading sheeting (*5*).

Legibility: A study has recommended the use of work zone signs with orange background, micro-prismatic materials, which provide far greater legibility distance than high-intensity ones (*6*). Micro-prismatic fluorescent orange materials were found to perform better than Type 3 (*1*).

Color: Speed variances tended to decrease at the midpoint and the taper with fluorescent signs relative to standard orange signs. The collision reduction in the overall traffic conflicts from what was expected at all treatment sites was about 7% (*6*).

Design Issues

Height of letters used depends on site characteristics such as operating speed (*1*).

Cross References

None.

Key References

1. Chrysler, S.T., Carlson, P.J., and Hawkins, H.G. (2003). Nighttime legibility of traffic signs as a function of font, color, and retroreflective sheeting. *Transportation Research Board 82nd Annual Meeting Compendium of Papers* [CD-ROM].

2 FHWA (2003). *Manual on Uniform Traffic Control Devices(MUTCD)*. Washington, DC.

3. Brich, S.C. (2002). *A Determination of the Appropriateness of Virginia's Retroreflective Sign Sheeting Specification for Fluorescent Orange Construction and Maintenance Signs*. Final Report (FHWA/VTRC 03-R5). Charlottesville: Virginia Transportation Research Council.

4. Russell, E.R., and Rys, M. (1992). *A Review of Kansas Department of Transportation's Reflective Sheeting Policy*. Final Report. Manhattan: Kansas State University.

5. Ahmed, S.A. (1991). *Evaluation of Retroreflective Sheetings for Use on Traffic Control Devices at Construction Work Zones*. Final Report. Stillwater: Oklahoma State University.

6. Hummer, J.E., and Scheffler, C.R. (1999). Driver performance comparison of fluorescent orange to standard orange work zone traffic signs. *Transportation Research Record, 1657*, 55-62.

DETERMINING WORK ZONE SPEED LIMITS

Introduction

Work zone speed limits refer to the reduced speed limits used in work zones to maintain safe traffic flow. Vehicle speeds in work zones are influenced by the geometrics of the roadway and the location of various work zone features such as lane closure tapers and work activity. Work zone speed limits within 10 mi/h of normal speed limits have more credibility and have been proven to be safer than speed limits that are 15 to 30 mi/h below the normal speed limit.

Design Guidelines

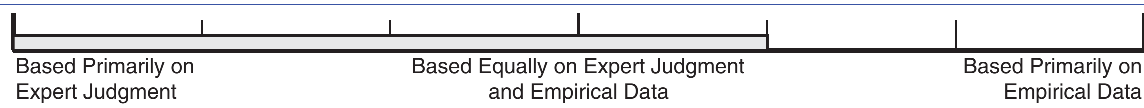
Speed and crash studies confirm that large speed limit reductions in work zones are undesirable (*1*). Speed limit reductions to 10 mi/h below the preconstruction speed limit resulted in the smallest increase in speed variance with the work zone—relative to the speed variance upstream of the work zone—of any of the speed limit strategies studied. Additionally, in rural freeway work zones involving work on or near the traveled way, a 10 mi/h reduction in the work zone speed limit minimized the crash rate increase from the preconstruction period to the construction period.

Speed Reductions and Speed Limit — A study has found that mean vehicle speed reductions were the greatest in work zones where the speed limit was not reduced, or at least not reduced more than 10 mi/h.

Speed limits need to be reduced only in the direction of traffic affected by the work zone when a wide median is between the directions of flow.

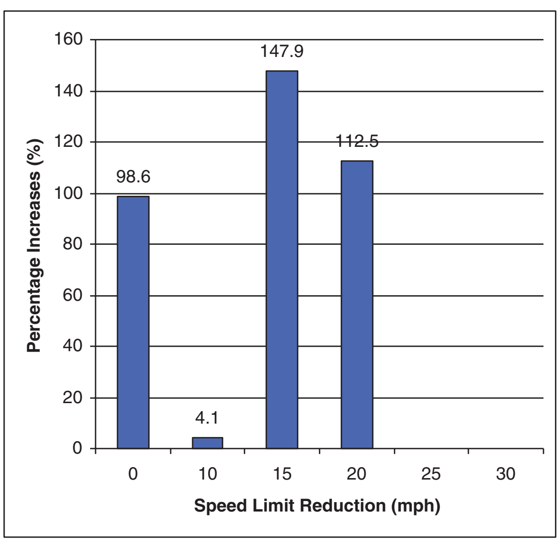
Lane Widths and Number of Lanes — Observed or achieved mean vehicle speed reduction appears to be highly correlated with the number of open lanes and lane widths.

Speed Display — CMSs with radar were successful in causing speeders to slow down in work zones. However, use of work zone speed limit signs with flash beacons produced mixed results.

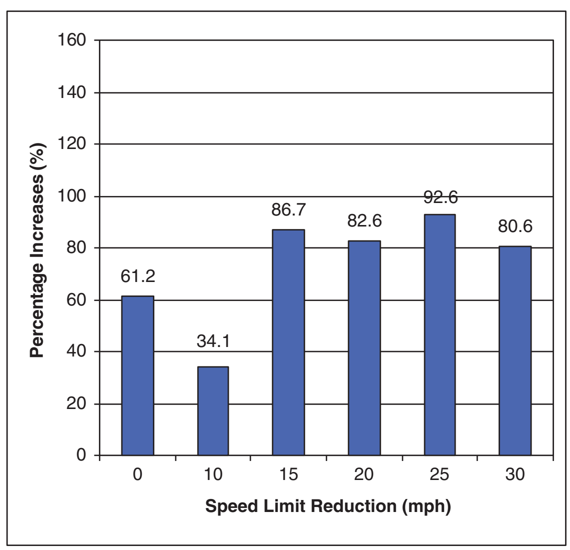


Speed considerations in work zones.

Increase in fatal plus injury crash rates from before construction to during construction.



Increase in speed variance from upstream of work zone to work zone.



Discussion

Speed reductions and speed limit: Studies have found that speed limit compliance decreased when the speed limit was reduced by more than 10 mi/h. Mean speeds were approximately 5 mi/h lower within work zones with no speed limit reduction than they were upstream of the same work zones. Speed limit compliance was found to be the greatest in work zones where the speed limit was not reduced (*1*). Another study noted that the mean and 85th percentile speeds were approximately 9 mi/h lower within the work zones of speed limit reductions of 10 mi/h than upstream of those same work zones and showed that the entire traffic stream uniformly reduced speeds (*2*). In general, speed reduction is better achieved when the work zone is well marked in advance of the work zone activity; motorists slow down out of self preservation and not the speed limit. Note that people drive the speed they feel comfortable with regardless of the posted speed limit if enforcement is not present (*3*), whereas speed reduction as high as 9.1 mi/h was observed with the presence of police (*4*).

Lane widths and number of lanes: Lane widths are directly related to speed reduction on roadways. For 11-ft lanes, speed reduction of 4.4 mi/h was observed to be 133% more than the value of 1.9 mi/h recommended by the *Highway Capacity Manual* (HCM) (*5*) for basic freeways. For 10.5-ft lanes, the observed reduction of 7.2 mi/h was 69% greater than the value of 4.25 mi/h recommended by the HCM (*6*). In addition, speed reduction appears to be highly correlated with the number of open lanes. Motorists tend to select higher speeds, regardless of the posted work zone speed limit, when more lanes are open to traffic (*7*).

Speed display: CMSs with radar were successful in effecting significant speed reduction in work zones. Also, no significant differences were found to exist in the speed reductions between vehicle types (*8*). However, another study found that the use of work zone speed limit signs with flashing beacons produced mixed results. Speed reductions were insignificant on urban arterials where commercial advertisements and other traffic control devices compete for drivers' attention (*9*).

Design Issues

A work zone speed limit may also be affected by restrictive geometric features such as curves or intersections.

Cross References

Influence of Speed on Sight Distance, 5-12

Key References

1. Migletz, J., Graham, J., Hess, B., Anderson, I., Harwood, D., and Bauer, K. (1998). *Effectiveness and Implementability of Procedures for Setting Work Zone Speed Limits*. Final Report, NCHRP Project 3-41(2). Independence, MO: Graham–Migletz Enterprises.
2. Sisiopiku, V.P., Lyles, R.W., Krunz, M., Yang, Q., Akin, D., and Abbasi, M. (1999). *Study of Speed Patterns in Work Zones*. East Lansing: Michigan State University.
3. Fors, C. (2000). Work zone ahead: reduce speed. *Roads and Bridges, 38*(1), 58-61.
4. Lyles, R.W., and Sisiopiku, V.P. (1999). *An Evaluation of Speed Control Techniques in Work Zones (Work Zones 2)*. East Lansing: Michigan State University.
5. Transportation Research Board (2000). *Highway Capacity Manual 2000*. Washington, DC.
6. Chitturi, M.V., and Benekohal, R.F. (2005). Effect of lane width on speeds of cars and heavy vehicles in work zones. *Transportation Research Record, 1920*, 41-48.
7. Sawaya, O.B., and Schofer, J.L. (2000). Speed up, or slow down. *World Highways/Routes Du Monde, 9*(6), 78-79.
8. Fontaine, M.D., and Garber, N.J. (1996). *Controlling Vehicle Speeds in Work Zones: Effectiveness of Changeable Message Signs With Radar* (UVA/529242/CE96/102). Charlottesville: University of Virginia.
9. Hall, J., and Wrage, E. (1997). *Controlling Vehicle Speeds in Highway Construction Zones* (NMSHTD-97-07). Albuquerque: University of New Mexico.

CHAPTER 14

Rail-Highway Grade Crossings

Forthcoming

CHAPTER 15

Special Considerations for Urban Environments

Forthcoming

CHAPTER 16

Special Considerations for Rural Environments

Forthcoming

CHAPTER 17

Speed Perception, Speed Choice, and Speed Control

Forthcoming

PART IV

Human Factors Guidance for Traffic Engineering Elements

CHAPTER 18

Signing

Forthcoming

CHAPTER 19

Variable Message Signs

Forthcoming

CHAPTER 20

Markings

Forthcoming

CHAPTER 21

Lighting

Forthcoming

PART V

Additional Information

CHAPTER 22

Tutorials

Tutorial 1: Real-World Driver Behavior Versus Design Models

Much of the information on sight distance presented in Chapter 5 reflects the application of empirically derived models to determine sight distance requirements. Such models, while valuable for estimating driver behavior across a broad range of drivers, conditions, and situations, have limitations.

This tutorial discusses how driver behavior as represented in sight distance models may differ from actual driver behavior. The design models presented in Chapter 5 use simplified concepts of how the driver thinks and acts. This simplification should not be viewed as a flaw or error in the sight distance equations. These models are a very effective way of bringing human factors data into design equations in a manner that makes them accessible and usable. After all, the intent of a sight distance equation is not to reflect the complexities of human behavior but to bring what we know about it into highway design in a concise, practical way. However, like any behavioral model, models for deriving sight distance requirements are not precise predictors of every case and there may be some limitations to their generality. Therefore, having an understanding of certain basic principles of human behavior in driving situations is useful to better interpret these models and to understand how they may differ from the range of real-world driving situations.

Sight distance formulas for various maneuvers (presented in Chapter 5) differ from one another, but they share a common simple behavioral model as part of the process. The model assumes that some time is required for drivers to perceive and react to a situation or condition requiring a particular driving maneuver (i.e., PRT), which is followed by some time (i.e., MT) and/or distance required to execute the maneuver. Sight distance equations for some maneuvers may contain additional elements or assumptions; however, all have this basic two-stage model somewhere at their core.

The two equations that follow show two versions of the general, two-component model. In both versions, the first term shows the distance traveled during the PRT component and the second term shows the distance traveled during the MT component. The difference is that the first equation shows a case where the distance traveled while executing the maneuver is based on the ***time*** required to make that maneuver (for example, the time to cross an intersection from a Stop), while the second equation shows a case where the distance traveled while executing the maneuver is based directly on the ***distance*** required to complete the maneuver (for example, braking distance for an emergency stop). For both forms of this general equation, vehicle speed (V) influences the second (MT) component.

The general form of the sight distance equation is:

$$d_{SD} = kVt_{prt} + kVt_{man}\text{, where maneuver time is input or}$$

$$d_{SD} = kVt_{prt} + d_{manV}\text{, where maneuver time is input}$$

Where:

d = required sight distance
V = velocity of the vehicle(s)
t_{prt} = PRT
t_{man} = MT
d_{manV} = distance required to execute a maneuver at velocity V
k = a constant to convert the solution to the desired units (feet, meters)

This model shows that the sight distance requirement is composed of (at least) two distances: there is a distance traveled while the driver perceives and evaluates a situation (determined by PRT and vehicle speed) and a distance traveled while executing the maneuver (determined by maneuver time/distance and vehicle speed). Figure 22-1 depicts the activities and sequence of activities associated with this simple model. As the figure shows, the PRT component is itself viewed as a series of steps. These individual steps are not explicit in the design equation but are included in the assumptions that underlie the PRT value. Design equations and their assumptions for specific maneuvers were discussed in Chapter 5. The sequential model of driver behavior shown in Figure 22-1 is a shared common conceptual underpinning of various sight distance equations.

However, in some respects, we can consider this model to be a “convenient fiction,” in part because it depicts a simple, fixed, linear, and mechanistic process. While the model provides a useful basis for deriving approximate quantitative values for design requirements that work for many situations, real-world driving behavior is far more complex than the model suggests. While highway designers and traffic engineers are often required to work with less complex (i.e., imperfect) models of human visual perception, attention, information processing, and motivation, it is important that they understand those factors that may affect the application of design sight distance models for specific situations. Such an understanding will help them to prevent, recognize, or deal with sight distance issues that may arise. For a particular situation, the standard sight distance design equation might either underestimate or overestimate the actual needs of a driver. Subsequent sections of this tutorial deal with specific factors that affect the driver response and provide guidance for working with them. Before these specific factors are considered, it will be useful to have an appreciation of how the simple driver models that underlie sight distance requirements contrast with the real complexities of driver behavior.

There are a number of factors or conditions associated with driver responses to a hazardous event or object that are not reflected in the basic sight distance model, but nonetheless can have a profound effect on driver behavior and overall roadway safety:

- Conditions or events that occur prior to a hazardous event/object becoming visible to the driver
- How and when the driver processes relevant information
- Driving as an “episodic” activity versus driving as a “smooth and continuous” activity
- The nature of the hazardous object or event
- The nature of the driver’s response
- Individual differences across drivers
- The quality and applicability of the empirical research used to develop the driver models

Each of these is discussed in more detail below.

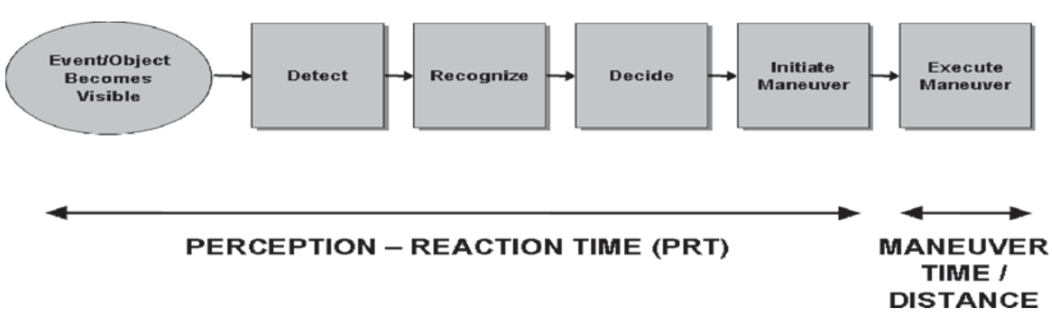


Figure 22-1. Diagrammatic version of the basic sight distance model.

Conditions or Events that Occur Prior to a Hazardous Event/Object Becoming Visible to the Driver

The model shown in Figure 22-1 is not sensitive to events that happen prior to the moment that the hazardous object or event becomes visible to the driver. In reality, the driver's ability to react to a hazardous object or event may be strongly influenced by previously occurring conditions or events. For example, drivers traveling on a roadway with few access points and little traffic may be unprepared to stop for a slow-moving vehicle ahead. In contrast, if drivers had been encountering numerous commercial driveways and intersections, with entering truck traffic, they might more readily react. Roadway design and operational features in advance of a hazardous event/object becoming visible are potentially important influences on behavior that are not explicit in the basic sight distance model. Figure 22-2 shows an expansion of the basic model, with added "driver state" factors (e.g., anticipation, situational awareness, caution, and locus of attention) that increase or decrease the driver's cognition preparation for a hazardous condition or event.

In Figure 22-2, an addition component to the model is shown prior to the event becoming visible. One element of the additional component is ***cognitive preparation.*** This general term encompasses the various active mental activities that can influence response times and decisions, such as driver expectancies, situational awareness, a general sense of caution, and where attention is being directed by the driver. Part II: Bringing Road User Capabilities into Highway Design and Traffic Engineering Practice provides some further explanation of these factors. As the arrows in the figure show, the driver's cognitive preparation as he or she encounters a hazardous object or event can influence the speed of detection, the speed and accuracy of recognizing the situation, and the speed and type of decision made about how to respond. The critical point is that the PRT associated with a particular hazardous object or event is influenced by the conditions or events preceding the driver's perception of the hazardous object or event.

The second element in the additional component in Figure 22-2 that occurs prior to the driver's perception of the hazardous object or event is ***speed selection.*** As discussed earlier, speed can have perceptual effects, influencing how easily a target object is detected or how accurately gaps are judged. Speed may affect the driver's sense of urgency, which can influence what maneuver options are considered and their relative appeal. Speed also may directly affect the difficulty, as well as the required time or distance, of the maneuver. Therefore, the driver's speed choice prior to the event may influence the driver's decision process; it may also influence the time available for the driver's response.

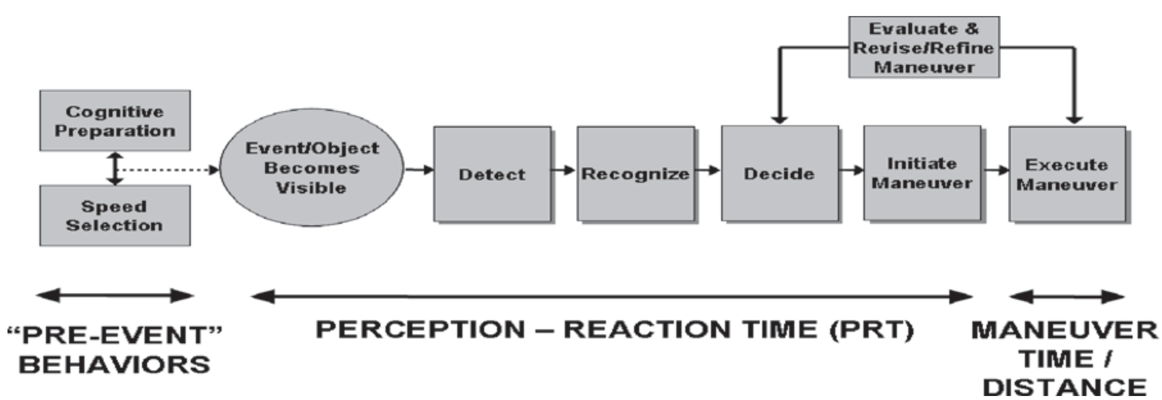


Figure 22-2. Added elements to basic sight distance behavioral model.

The basic sight distance behavioral model (Figure 22-1) makes assumptions about driver cognitive state and speed choice as the hazardous event is encountered. In reality, the driver does not arrive at the situation as a "blank slate." The locus of a sight distance problem, or its solution, therefore may turn out to be in advance of the problem site itself.

How and When the Driver Processes Relevant Information

The basic sight distance model shows a chain of mental and physical events taking place in the following sequential fashion:

1. A hazardous object or event becomes visible.
2. The presence of this object or event is detected by the driver.
3. The object or event is recognized and understood by the driver.
4. The driver makes a decision about what maneuver is needed to avoid or respond to the object or event.
5. The maneuver is initiated.
6. Once initiated, the maneuver is fully executed.

Each event in this chain takes some amount of time to occur, and—according to the basic model—one step does not begin until the previous step is complete. This assumed "serial processing" model is indeed one way a driver might respond, but it may not be typical. For example, if a driver sees some vague object ahead of the vehicle that might or might not be in the roadway, he or she may begin to brake even before the object is fully recognized. Also, once the object is fully recognized, the maneuver may be reconsidered (e.g., stopped, slowed, accelerated, or otherwise revised). Contrary to the serial processing assumed by the basic model, the mental processes shown by the various boxes in Figure 22-1 may actually occur in parallel, in a different sequence, or with modifications (feedback loops) as the process progresses. The assumed linear response sequence is therefore really a simplified case used for design purposes. It should not be viewed as a universal or invariant representation of the more complex perceptual and cognitive activity in complex driving situations.

Importantly, consistency in geometric design is required in order to meet driver expectations and to avoid surprising the driver.

Driving as an "Episodic" Activity versus Driving as a "Smooth and Continuous" Activity

Related to the previous point, the basic sight distance model reflects an "episodic" perspective of real-world driving. That is, some object or event becomes visible, and some driver maneuver(s) in response to the object or event are initiated and executed. Then, another object or event becomes visible, and another maneuver takes place. Real-world driving however, is normally smooth and continuous; it is not a jerky sequence of separate, individual episodes. Yet for ease of analysis, we often break driver behavior into individual events each requiring their own separate response, or we treat the roadway as a succession of discrete segments or zones. To the driver, though, the roadway and the driving task are generally smooth and continuous. Real drivers do not just react to events that randomly occur; they plan and predict and manage and adapt to events as they go along. Adopting an "episodic" perspective is useful for developing models of driver behavior that are both simple and reasonably predictive. A "smooth and continuous" perspective of real-world driving is much more difficult to model and quantify, especially in a manner that will easily generate a simple design parameter. From a human factors perspective, sight distance models are based on a little bit of driver performance data that describe how a driver *might* react, but may not reflect how drivers always or even typically behave. The use and application of the simpler sight distance model is generally reasonable from a design perspective, however, because it is somewhat conservative. Specifically, those drivers who encounter a situation without planning or anticipation are those most likely to be in need of the full sight distance requirement.

The Nature of the Hazardous Object or Event

For each sight distance design application, the analysis is based around some object, event, or roadway feature to which the driver must respond with a driving maneuver. That object, event, or roadway feature might be debris in the roadway, braking by a vehicle ahead, an approaching vehicle on a conflicting path, a freeway lane drop, a change in signal phase, a pedestrian entering the road, a railroad gate, an animal, a vehicle entering from a driveway, or many other things. The PRT process begins with the potentially hazardous object or event (the "visual target") becoming visible to the driver followed by some time to visually detect and recognize that target. Design equations have to include some estimate of when a target becomes visible and how long driver reaction will take. The many examples of potential hazards suggest just how different these may be as visual targets; therefore, making a single assumption is an obvious simplification. A target object may be large or small, bright or dull, familiar or unfamiliar, moving or stationary, or have other attributes that affect the driver's ability to accurately and quickly detect and recognize it. Explicitly or implicitly, design equations have to make some assumption about the characteristics of the visual target. Furthermore, visibility conditions may vary with weather, glare, light condition, roadway lighting, and intervening traffic (especially truck traffic). Again, design equations must be based on some assumption about visibility conditions.

A PRT model requires the user to be able to specify the point in time or space that the hazard becomes visible to the driver. However, this too may be an oversimplification. For example, there is usually no sharp threshold where an object in the road suddenly goes from being invisible to visible. Most hazards do not occur all at once, but evolve over some time, such as a vehicle moving into a lane in front of a driver. Some events might have a preview, such as a vehicle positioned in a driveway prior to its pulling out or children playing near the road prior to entering the road. Some events might have multiple cues; for example, a freeway lane drop has an initial taper, lane markings, and the point where the lane finally disappears. Sometimes the important visual target is not the hazard object or event itself but a cue about the hazard; for example, brake lights on a vehicle ahead may be a warning cue about a sudden severe deceleration, but they may also reflect a minor tap on the brake. Drivers cannot respond to the brake light in the same way they respond to recognition of the actual deceleration.

Overall then, the driver's response to a hazardous event or object will reflect specific physical characteristics, visibility conditions, and the evolving nature of the hazard itself.

The Nature of the Driver's Response

The behavioral components of sight distance models are based around some very specific maneuver in response to the object/event, with fixed assumptions about response parameters. For example, when responding to an unexpected need to stop, AASHTO (2004) assumes a braking maneuver with a deceleration of 3.4 m/s^2 (11.2 ft/s^2). Braking may be a reasonable response to assume, and 3.4 m/s^2 may be a reasonable deceleration to assume, but this certainly does not mean that braking at this level is always the driver's response to an unexpected hazard. The maneuver time and maneuver distance components of sight distance models are in many cases based on good empirical research and human factors considerations and work well for most applications. Still, the use of a single standard value is a convenient simplification. Actual maneuvers can be influenced by various factors. The perceived urgency of the situation (based on available time/

distance, driver/vehicle capabilities) determines options and shapes the way drivers respond, and often multiple options are available to the driver. For example, for an unanticipated stop, a driver may brake severely, or brake gradually and steer around, or swerve sharply. The surrounding physical, traffic, and social environment will affect these options: is there a lane or shoulder to steer around, are there adjacent or following vehicles, is the obstacle a piece of debris or a child, is there a passenger in the vehicle? Drivers also make trade-offs between speed versus control when executing maneuvers. The AASHTO deceleration value of 3.4 m/s^2 represents an estimate of a "comfortable deceleration" with which almost all drivers can maintain good vehicle control. In this sense it is appropriate for general design, but does not necessarily describe what drivers can do or actually do under all conditions or circumstances. Furthermore, once a driver initially selects and begins to execute a particular maneuver, the maneuver is not simply executed in a fixed manner. As Figure 22-2 illustrates, the situation is monitored and the maneuver is re-evaluated as it is being executed. The response may be refined or modified as it progresses. Drivers may not respond to a situation with a maximum response (e.g., maximum braking or steering), but may initiate a more controlled action and monitor the situation before committing to a more extreme action. For instance, they may begin gradual braking and check their mirrors for following traffic before decelerating more sharply or swerving.

Individual Differences Across Drivers

The diverse driving population ranges widely in capabilities and behaviors. Drivers vary in experience, visual acuity, contrast sensitivity, useful field of view, eye height, information processing rate, tolerance for deceleration, physical strength, and other factors related to PRT and MT. A design equation will typically be based around a design driver with some assumed set of attributes. To be conservative, the assumptions do not usually represent a typical driver, but rather reflect less capable drivers (e.g., 15th percentile in terms of some attribute). Assumptions are made about the state of the driver as well. For example, data are generally based on drivers who are sober and alert. Yet impaired or fatigued drivers may represent a large part of the crash risk. Alcohol, drugs, medication, and fatigue can have dramatic effects on the psychological processes that underlie PRT and MT. Driver distraction by activity within the vehicle is also a common occurrence that is not reflected in the design model. In-vehicle technologies, such as cell phones, navigation systems, and infotainment systems, are increasingly common. The multitasking driver is an increasing concern, but PRT models do not reflect this possibility.

The Quality and Applicability of the Empirical Research Used to Develop the Driver Models

The values used in design equations may or may not be derived from good empirical sources. In some cases (e.g., brake reaction time), there are numerous empirical studies and reasonably good agreement among them. In other cases, empirical data are very limited, are of lesser quality, or are only weakly applicable to the design issue in question. The quality and applicability of the numbers that come from empirical studies are sometimes questionable on a number of grounds: the sample of drivers may be small or unrepresentative; the situations evaluated may be limited and may not generalize well; the research may be out of date (given changes in roadways, traffic, vehicles, traffic control devices, and driver norms); the research setting (test track, simulator, laboratory) may lack validity; and results may conflict with results from other studies. It would be wrong to assume that sight distance design equations are necessarily based on a strong, high-quality empirical foundation that readily generalizes to all cases.

Another concern related to data quality and applicability is the inability of general design equations based on simple behavioral models to incorporate site-specific considerations. Empirical observations made at the site may be at variance with the predicted behaviors. Even when design equations are based on "good" data, the generality of the models suggests that credence should be given to any empirical data that can be collected at the site itself.

In summary, sight distance requirements are based on a highly simplified and mechanistic model of driver behavior and capabilities. This approach is reasonable and generally successful. The general assumptions often work well enough to approximate the needs of most drivers; however, it is important to recognize that this simple model has a number of limitations as a description of actual driver performance. When difficult sight distance problems are being diagnosed or addressed, it may be useful for the highway designer or traffic engineer to recognize how design models simplify driver actions and to acknowledge the realities of more complex driver perception and behavior.

Tutorial 2: Diagnosing Sight Distance Problems and Other Design Deficiencies

Introduction

The previous sections of this document—especially Chapter 5—have provided design guidelines for human factors aspects of various sight distance concepts. However, for users to implement these guidelines in a practical sense, it is desirable to provide a procedure for their operational application. Therefore, this section comprises a hands-on tool whereby practitioners can apply human factors techniques to analyze sight distance problems and other design deficiencies at a selected highway location.

A starting point for development of the current procedure was a review of previously documented procedures for conducting on-site driving task analyses (Alexander & Lunenfeld, 2001) that applied techniques such as commentary drive-thru procedures to generate checklist subjective-scaled ratings of hazard severity and information load. The current in-situ sight distance diagnostic procedure includes application of previously available engineering tools, e.g., AASHTO (2004) analyses of geometric requirements and MUTCD (FHWA, 2003) traffic control device requirements, and augments these techniques with those sight distance concepts presented in Chapter 5 of this HFG.

This sight distance diagnostic procedure consists of a systematic on-site investigation technique to evaluate the highway environment to support the concepts of interest, i.e., SSD, PSD, ISD, and DSD. The highway location is surveyed, diagrammed, and divided into component sections based on specific driving demands (e.g., requirement to perform a maneuver). Then each section is analyzed in terms of its suitability to support the required task (e.g., information provided to driver and allotted time to the complete required task). This procedure enables the practitioner to compare the *available* sight distance with the *required* sight distance to safely perform the driving task.

The Six-Step Procedure

The procedure consists of the following six steps:

1. Collect field data to describe roadway characteristics and other environmental factors affecting sight distance requirements and driver perception of a potential hazard.
2. Conduct engineering analyses applying traditional techniques, e.g., AASHTO design criteria and MUTCD compliance, to initially assess site characteristics or deficiencies.
3. Examine crash data and prepare collision diagram to seek possible association between safety and a sight distance problem.
4. Establish component roadway sections in which drivers respond to specific visual cues in order to initiate a maneuver to avoid a hazard.
5. Analyze driving task requirements (PRT and MT) and determine the adequacy of each component roadway section to support these requirements.
6. Develop engineering strategies for improvement of sight distance deficiencies.

A flow diagram overview of the process is shown in Figure 22-3. Following the description of the six-step procedure, an example application is provided.

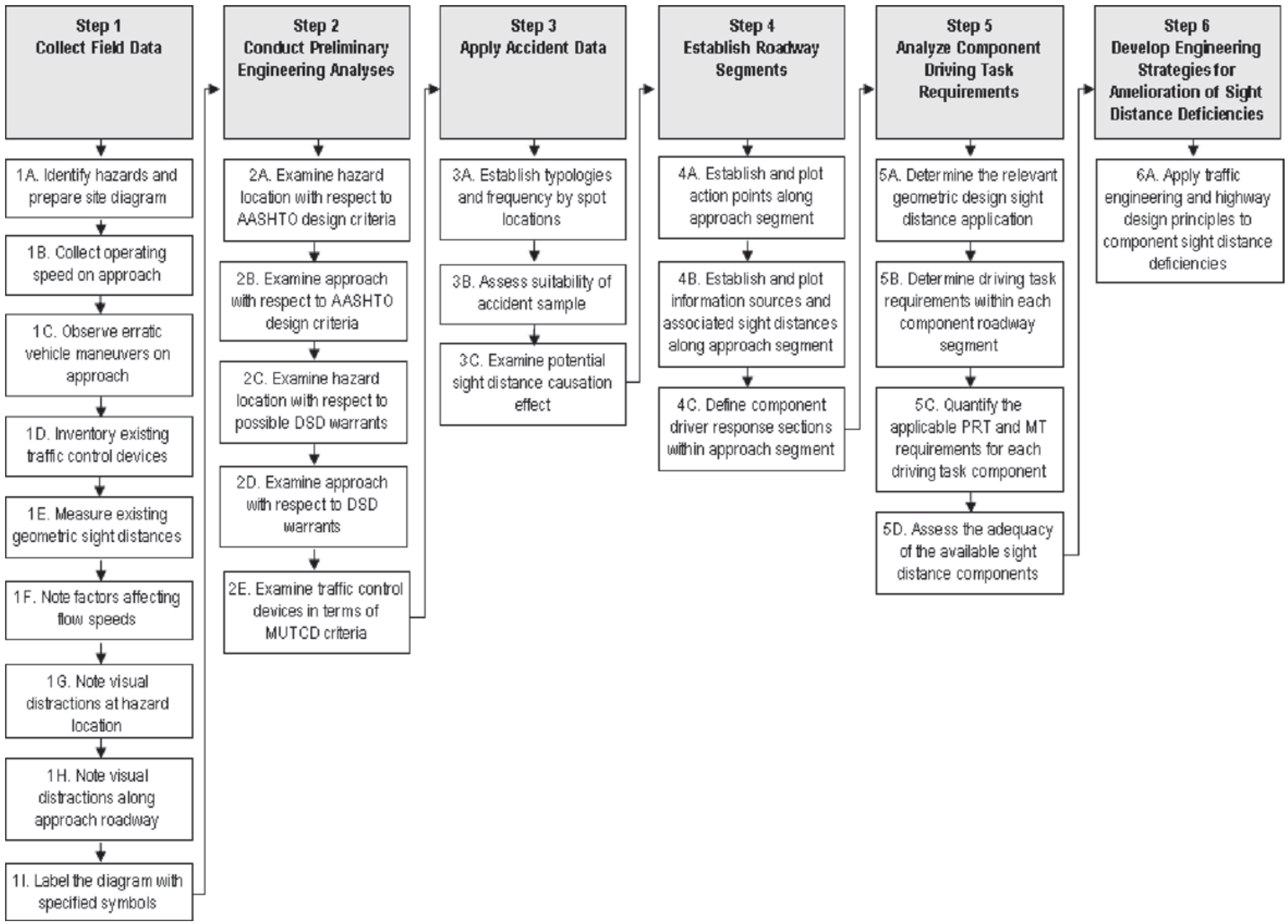


Figure 22-3. Flow diagram of six-step diagnostic process.

Step 1: Collect Field Data

This step involves making specific field measurements and observations. Data are to be gathered both at the location of the designated hazard as well as the approach roadway section immediately in advance of the hazard. Approach distances over which field measurements should be gathered are determined from Table 22-1 at the end of this step. Approach distances were derived from approximated perception-reaction and sign reading times applied to the designated operating speeds.

Step 1A: Identify Hazard and Prepare Site Diagram

Procedure	Product/Application
The specific hazard location under investigation is identified and the approach roadway is diagrammed. Example of hazards requiring sight distance consideration and the associated sight distance concepts are as follows. • A hidden intersection (SSD) • An exit from a shopping mall in a heavily lit (e.g., visually cluttered) setting (DSD) • A vehicle approaching an intersection (ISD) • An oncoming vehicle in a passing zone (PSD) Note distances from hazard to the following features: (1) traffic control devices, (2) intersecting driveway or roadways, and (3) sight distance obstructions.	***References:*** Lunenfeld, H., and Alexander, G. J. (1990). *A User's Guide to Positive Guidance* (FHWA-SA-90-017). Washington, DC: FHWA.

Step 1B: Collect Operating Speed on Approach

Procedure	Product/Application
Spot speeds for randomly selected vehicles are to be observed at a sufficient advance distance upstream from the hazard beyond which slowing in response to the hazard is expected. Candidate speed collection techniques are radar/laser detection, automated speed recorders, and manual timing. References noted in the column to the right describe appropriate procedures to ensure random vehicle selection and suitable sample sizes. In the event that the approach roadway section is characterized by horizontal or vertical curvature, speed collection points should be selected so as to represent operational speeds at these locations.	The product of this step will be a statistical distribution of speeds from which means and/or percentile values will be applied to estimate vehicle speed for the approach roadway under study. ***References:*** Hanscom, F. R. (1987). Validation of a non-automated speed data collection methodology. *Transportation Research Record, 1111,* 54–61. Robertson, H. D. (Ed.). (2000) *Manual of Transportation Engineering Studies,* Washington, DC: Institute of Transportation Engineers.

Step 1C: Observe Erratic Vehicle Maneuvers on Approach

Procedure	Product/Application
Observations of vehicle movements should be considered in situations of sufficiently high traffic volumes to justify this type of study, e.g., 100 vehicles per hour (vph) and above. Typical target vehicle behaviors indicative of a sight distance problem are sudden slowing (e.g., observable break light activation) and abrupt lane changes when these maneuvers are not induced by other vehicles in the traffic stream. A considerable literature base is available regarding the conduct and interpretation of "traffic conflicts" studies; however, the reader is cautioned that traffic conflicts studies are limited to interactions between vehicles. A sight distance–induced erratic maneuver, on the other hand, can involve a single vehicle. Methodological literature addressing conflicts study is helpful with respect to observational techniques.	The outcome of this step should be insightful with respect to possible sight distance–induced vehicle behaviors. ***References:*** Parker, M. R., and Zegeer, C. V. (1989). *Traffic Conflict Techniques for Safety and Operations* (FHWA-IP-88-026 (*Engineer's Guide*) and FHWA-IP-88-027 (*Observer's Guide*)). Washington, DC: FHWA. Taylor, J. I., and Thompson, H. T. (1977). *Identification of Hazardous Locations: A Users Manual* (FHWA-RD-77-82). Washington, DC: FHWA.

Step 1D: Inventory Existing Traffic Control Devices

Procedure	Product/Application
Document existing signs, signals, and pavement markings along with their respective distances from the hazard under study. Document the age of these signs, signals, and markings, as well. The letter heights and mounting heights of signs need to be recorded. Document any visual obstructions.	The resulting device inventory will be subsequently applied in this diagnostic analysis to evaluate the suitability of provided information, as well as visual distractions and information processing demands on motorists as they approach the hazard under study.

Step 1E: Measure Existing Geometric Sight Distances

Procedure	Product/Application
Existing geometric sight distance limitations along the approach to the hazard must be measured in accordance with AASHTO criteria. Specifically, sight distance observations should be made from an elevation above the pavement that equals the design driver eye height (i.e., 3.5 ft) to a point ahead that is 2.0 ft above the pavement.	This step will yield the length of specific roadway subsections along the approach in which drivers must observe and process available information (e.g., roadway features and other vehicles). ***References:*** AASHTO (2004). *A Policy on Geometric Design of Highways and Streets*. Washington, DC.

Step 1F: Note Factors Affecting Flow Speeds

Procedure	Product/Application
Certain roadway environmental features are known to affect drivers' selection of speed. Examples are pavement defects, narrow shoulder widths and protruding bridge piers, abutments, guardrails, median barriers, etc.	Documentation and general awareness of these factors are important because subsequent minor highway improvement projects may result in higher highway speeds, thus producing increased sight distance requirements.

Step 1G: Note Visual Distractions at Hazard Location

Procedure	Product/Application
Certain environmental conditions are known to produce "visual clutter" (i.e., distractions that make hazards more difficult for drivers to perceive). Examples include (1) off-roadway lighting, (2) commercial signing in driver field of view, (3) complex urban intersection designs, (4) high volumes of vehicular/ pedestrian movement (including bicycles), and (5) proliferation of intersection traffic control devices. Observations should document drivers' field of view at SSD from hazard (e.g., AASHTO (2004)).	This inventory of visual distractions will be subsequently applied in a human factors analysis to determine the applicable sight distance criterion (e.g., DSD, to address driver perception and information-processing time requirements at the hazard location). ***References:*** AASHTO (2004). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.

Step 1H: Note Visual Distractions Along Approach Roadway

Procedure	Product/Application
As in Step 1G, visual environmental conditions along the approach to the hazard also may produce driver distractions. These need to be included in the field data collection process. Observations should document drivers' field of view at DSD from hazard (e.g., AASHTO (2004)).	This inventory of visual distractions will be subsequently applied in a human factors analysis to determine the applicable sight distance criterion to address driver information-processing time requirements on the approach to the hazard location. ***References:*** AASHTO (2004). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.

Step 1I: Label the Diagram with Specified Symbols

Procedure	Product/Application
SD$_{HAZ}$—*Sight distance to a potential hazard.* The point at which a location or object is first detectable to an approaching motorist. **A**—*Point of required action.* The location where an intended maneuver (e.g., hazard avoidance) is to be completed. **SD$_{TCD}$**—*Sight distance to a traffic control device.* The point at which the device is first detectable to an approaching motorist. **TCD**—*Traffic control device.* The location of the device that warns of the hazard, measured as a distance from the location or object about which information is provided.	The inclusion of uniform symbols on the site diagram will facilitate the subsequent sight distance analysis (see Figure 22-4).

Table 22-1. Recommended approach distance to hazard for collection of field data.

Estimated Operational Speed (mi/h)	Approach Distance to Hazard (ft)		
	Visually Cluttered Environment	Visually Non-Cluttered Environment	Additional, when TCDs Present
25	360	180	95
30	440	220	110
40	580	290	150
50	730	370	185
60	880	440	220
70	1030	520	260

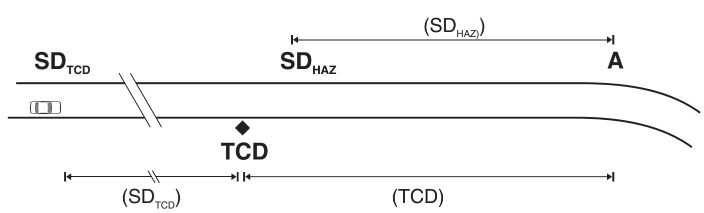


Figure 22-4. Example symbol diagram: A two-lane 55-mi/h roadway approaches a 35-mi/h curve.

Step 2: Conduct Preliminary Engineering Analyses

This step involves the application of traditional traffic engineering techniques (e.g., AASHTO Design Policy geometric design criteria and DSD warrant) as a preliminary determinant of site deficiencies. In addition, the placement of traffic control devices needs to be examined in terms of MUTCD requirements.

Step 2A: Examine Hazard Location with Respect to AASHTO Design Criteria

Procedure	Product/Application
To ensure a valid engineering diagnosis of sight distance to a hazard, it is necessary to first assess whether the hazard location itself has any inherent design shortcomings. One geometric deficiency potentially associated with a hazard location might be roadside that fails to meet requirements of the AASHTO *Roadside Design Guide*. Other examples are (1) a high-crash intersection may be deficient with respect to existing corner sight distance (AASHTO, 2004) and (2) in the case of a high incidence of run-off-road crashes, observed operational speeds (from Step 1A above) may differ significantly from the design speed upon which the curve radius and super elevation of the curve under consideration were based (AASHTO, 2004).	The resulting analytical steps ensure that the hazard location itself is free of any inherent design shortcomings that have the potential for confounding the intended sight distance diagnosis. ***References:*** AASHTO (2002). *Roadside Design Guide.* Washington, DC. AASHTO (2004). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.

Step 2B: Examine Approach with Respect to AASHTO Design Criteria

Procedure	Product/Application
As with the procedure noted in Step 2A, to ensure the integrity of the overall sight distance diagnosis, it is necessary to assess whether the approach to the hazard location has any inherent design shortcomings. (For example, a substandard lateral clearance to a roadside object along the approach may create a visual obstruction, thus producing an unintended sight distance limitation.) Likewise, crest vertical sight distances along the approach should be consistent with observed operational speeds gathered during Step 1B.	The resulting analytical steps ensure that the approach to the hazard is free of any inherent design shortcomings that have the potential for confounding the intended sight distance diagnosis.

Step 2C: Examine Hazard Location with Respect to Possible DSD Warrants

Procedure	Product/Application
AASHTO (2004) (e.g., section on DSD) notes a distinction between typical stopping sight distances and those in which drivers are required to make complex decisions (i.e., in which drivers require PRT beyond the design value [which is typically 2.5 s]). The DSD criterion applies to a difficult-to-perceive information source in a roadway environment that may be visually cluttered. Therefore, the hazard location needs to be examined for conditions of "visual noise" from competing sources of information (e.g., roadway elements, traffic, TCDs, and advertising signs). Specific sources of visual clutter were also noted in Step 1E.	When DSD-warranting conditions are found to exist, apply the sight distance requirements noted in AASHTO (2004), rather than conventional stopping distances based on a 2.5-s PRT. ***References:*** AASHTO (2004). *A Policy on Geometric Design of Highways and Streets.* Washington, DC.

Step 2D: Examine Approach with respect to DSD Warrants

Procedure	Product/Application
The approach to the hazard location also must be examined for conditions of visual clutter meeting requirements for DSD application. In particular, these conditions could take the form of roadside distractions and/or complex TCDs at intersections along the approach.	Visual clutter along an approach to a hazard detracts from drivers' perception of the hazard. When DSD-warranting conditions are found to exist along an approach to a hazard, the distraction is sufficient such that available sight distance to the hazard must be restricted to that distance beyond the distraction.

Step 2E: Examine Traffic Control Devices with Respect to MUTCD Criteria

Procedure	Product/Application
The MUTCD (FHWA, 2003) prescribes device placement criteria for signs, signals, and markings. Devices at both the hazard location and along the approach need to be examined for MUTCD compliance. Note that the MUTCD establishes mandatory, recommended, and optional requirements for the application of TCDs. The examination conducted in this step (as well as Steps 4 and 5) should reflect these MUTCD criteria.	The output of this step will reveal whether inadequate traffic control device application (e.g., insufficient warning distance or inappropriate warning message) constitutes possible sources of driver confusion. Inappropriate or inadequate TCD information can result in longer information processing times, thereby creating an artificial sight distance problem. ***References:*** FHWA (2003). *Manual on Uniform Traffic Control Devices (MUTCD)*. Washington, DC.

Step 3: Apply Crash Data

This step involves the integration of traffic crash data into the analysis. The objective is to locate specific crash-prone locations within the roadway segment, which may be indicative of sight distance problems. The practitioner is cautioned that the absence of crashes does not rule out the existence of a sight distance problem, as crashes are probabilistic events and reporting requirements are variable.

Step 3A: Establish Typologies and Frequency by Spot Locations

Procedure	Product/Application
A review of crash data will reveal the occurrence of various types in close vicinity to the hazard under study. The associated pre-collision paths and their proximity to highway features may suggest the existence of a sight distance problem. Certain crash types are typically associated with specific sight distance problems: • Run-off-road, fixed-object crashes (SSD) • Side-swipe, rear-end crashes (PSD) • Right-angle, rear-end crashes (ISD)	A collision diagram is used to summarize crash types by location. For examples, see Robertson et al. (2000) and Hostetter and Lunenfeld (1982). ***References:*** Robertson, H. D., Hummer, J. E., and Nelson, D. C. (Eds.) (2000). *Manual of Transportation Engineering Studies.* Washington, DC: ITE. Hostetter, R. S., and Lunenfeld, H. (1982). *Planning and Field Data Collection (FHWA-TO-80-2).* Washington, DC: FHWA.

Step 3B: Assess Suitability of Crash Sample

Procedure	Product/Application
While well-documented procedures exist to statistically establish crash causation (see Council et al. (1980)), this level of sophistication is not necessary for the diagnosis of a sight distance problem. It is desirable (to the extent possible based on available crash data) to establish causation inferences based on crash patterns and to rule out non-sight-distance causal effects.	A reasonable level of confidence (albeit logic-based rather than statistically rigorous) regarding crash causation is possible based on the following: • Inferences based on crash patterns rather than a single event • Occurrences whereby non-sight-distance factors can be logically ruled out. ***References:*** Council, F. M., Reinfurt, D. W., Campbell, B. J., Roediger, F. L., Carroll, C. L., Dutt, A. K., and Dunham, J. R. (1980). *Accident Research Manual* (FHWA-RD-80-016). Washington, DC: FHWA.

Step 3C: Examine Potential Sight Distance Causation Effect

Procedure	Product/Application
Certain patterns of crash behaviors (i.e., pre-collision maneuvers) are suggestive of sight distance problems: for example, single-vehicle or run-off-road crashes with a fixed object that may appear visible under some conditions but may not be easily detectable to drivers during conditions of more limited visibility (e.g., darkness). These patterns need to be examined to determine whether sight distance is a potential causal factor (i.e., adequate nighttime sight distance conveyed by TCDs).	A collision diagram can be descriptive of the location and nature of a sight distance hazard, thus supporting a hypothesis regarding the effect of a sight distance problem.

Step 4: Establish Roadway Segments

The practitioner specifies component roadway approach segments in a manner to support the detailed human factors analysis in Step 5. Separate approach roadway segments are theoretically required for driver PRT and hazard avoidance maneuver functions. The product of this section is a series of driver task diagrams that depict the point where driver actions are required to avoid a potential hazard, information sources that warn of the hazard, and drivers' available sight distances to perform the necessary information-processing and maneuver tasks.

Step 4A: Establish and Plot Action Points Along Approach Segment

Procedure	Product/Application
Specific locations within the study roadway section requiring a driver action (e.g., maneuver) will be identified and plotted. For example, the hazard under study is the key point where action (e.g., driving at the posted speed) is likely required. Where a maneuver (e.g., decelerating) is necessary prior to reaching the hazard, the "compliance point" is the point where the maneuver is initiated (e.g., start of the deceleration distance). In the event that the approach roadway section requires some intermediate action (e.g., merging from a dropped traffic lane), this action also needs to be identified and plotted. Action points on the site diagram prepared in Step 1 should be indicated on the diagram by the symbol **A.** A series of sequential action points may be designated as $\mathbf{A_1}$, $\mathbf{A_2}$, etc.	The developed site diagram will indicate specific points where vehicle actions are required. Examples are as follows: • Approach maneuver (such as slowing) as required by the hazard under study • Any intermediate actions (e.g., required lane change) on the approach to the hazard under study

Step 4B: Establish and Plot Information Sources and Associated Sight Distances Along Approach Segment

Procedure	Product/Application
Any driver action (e.g., hazard avoidance) must be based on information available to the driver. In this step, drivers' information sources that inform an intended action must be located and documented. Information to the driver should be available from (1) detection of the hazard and/or (2) traffic control devices pertaining to the hazard. The following information/detection sources were noted on the site diagram in Step 1I: • Initial point of sight distance to the hazard identified by the symbol $\mathbf{SD_{HAZ}}$ • Location of TCD providing information regarding the hazard identified by the symbol **TCD** • Initial point of sight distance to the applicable TCD identified by the symbol $\mathbf{SD_{TCD}}$ In this step, separate plots of component information-processing segments may be helpful.	The developed site diagram will indicate specific points where information pertaining to the hazard is available to the driver. Examples are as follows: • Point of initial detection opportunity on an approaching of both the hazard and any traffic control device warning of the hazard. • Specific locations of any TCDs advising of the hazard. NOTE: In the event that the hazard under study is not detectable (i.e., defined in the visual field), the symbol $\mathbf{SD_{HAZ}}$ would not appear on the diagram. In such instances the required sight distance to action point (**A**) will be determined in Step 5.

Step 4C: Define Component Driver Response Sections Within Approach Segment

Procedure	Product/Application
Distinctly different driver information-processing tasks are associated with each detection and maneuver activity. In this step, roadway sections will be designated and plotted to illustrate the required travel distances over which the driver would perform these varied information-processing and maneuver tasks. Depending upon physical characteristics of the roadway section under study, four distinct driver response cases are possible: **Case 1:** Direct line of sight to hazard $\mathbf{SD_{HAZ} \rightarrow A}$ **Case 2:** Intervening traffic control device (i.e., warning of hazard) $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$ **Case 3:** Intervening (e.g., distracting) hazard ($\mathbf{A_2}$) within sight line of first hazard ($\mathbf{A_1}$) $\mathbf{SD_{HAZ1} \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$ **Case 4:** Intervening traffic control device and distracting hazard $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$	The product of this step is a diagrammed set of roadway component sections, each corresponding to specific information-processing and maneuver driver tasks. The distance over which a driver can react to a detectable hazard is the roadway section $\mathbf{SD_{HAZ} \rightarrow A}$**.** In this roadway section, the driver would detect the hazard and perform any required preparatory maneuver (e.g., decelerating). Likewise, the distance over which a driver reacts to an advance traffic control device is the roadway section $\mathbf{SD_{TCD} \rightarrow TCD}$. In this roadway section, the driver has the opportunity to detect the sign and comprehend the sign's message. The message becomes readable at the point $\mathbf{LD_{TCD}}$ (i.e., the legibility distance from the sign), which will be computed and located during Step 5. In the final approach section to the hazard, $\mathbf{TCD \rightarrow A}$**,** the driver would complete the decision-making and maneuver tasks.

Step 5: Analyze Component Driving Task Requirements

In this step, the practitioner applies human factors principles (comprising information-processing and decision-making criteria) to ensure the adequacy (or to quantify the shortcoming) of the approach roadway to allow for time/distance hazard avoidance requirements.

Step 5A: Determine the Relevant Geometric Design Sight Distance Application

Procedure	Product/Application
The analysis of driving task requirements involves application of the appropriate sight distance value for the given task. Sight distance requirements (to accommodate both the information-processing and maneuver tasks) approaching action points (**A**) will fall into one of the following categories (depending upon roadway environment condition), which were identified in Section 5.2: • Stopping sight distance (SSD) • Intersection sight distance (ISD) • Decision sight distance (DSD) • Passing sight distance (PSD)	The result of this task is the specification of the applicable procedure (e.g., engineering design formula) for the computation of $\mathbf{SD_{HAZ}}$ corresponding to each identified hazard or action point. The required sight distance based on application of the appropriate design formula is applied to determine the required length of the roadway segment under study.

Step 5B: Determine Driving Task Requirements Within Each Component Roadway Segment

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Procedure

Driver information-processing demands vary as a function of environmental factors, according to the four cases indicated below. Identify separate PRT and MT components of the driving task for each of the four cases. Specific values of PRT and MT will be determined subsequently.

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Case 1:
Direct line of sight to hazard; no traffic control
$\mathbf{SD_{HAZ} \rightarrow A}$

In this case, PRT and MT are determined from Section 5.2.

Case 2:
Intervening traffic control device (i.e., warning of hazard)

$\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$

1. Driver must detect traffic control device: $\mathbf{SD_{TCD} \rightarrow LD_{TCD}}$
2. Driver must read or otherwise comprehend message and may begin decision process: $\mathbf{LD_{TCD} \rightarrow TCD}$ (Legibility distance will be determined in Step 5C.)
3. Decision and maneuver must be completed: $\mathbf{TCD \rightarrow A}$

</td><td>

Case 3:
Intervening, distracting hazard at $\mathbf{A_2}$ within sight line of first hazard at $\mathbf{A_1}$

$\mathbf{SD_{HAZ1} \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$

1. Driver requires longer PRT due to complex visual scene ahead: $\mathbf{SD_{HAZ1} \rightarrow SD_{HAZ2} \rightarrow A}$ Consider DSD application.
2. Driver may require longer MT due to complexity of maneuver and visual scene: $\mathbf{SD_{HAZ2} \rightarrow A_2 \rightarrow A}$

Case 4:
Intervening traffic control device and distracting hazard at A_2 within sight line of first hazard A_1

$\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$

1. Driver must detect traffic control device: $\mathbf{SD_{TCD} \rightarrow LD_{TCD}}$
2. Driver must read or otherwise comprehend message and may begin decision process: $\mathbf{LD_{TCD} \rightarrow TCD}$
3. Driver may require longer MT due to complexity of maneuver and visual scene: $\mathbf{SD_{HAZ2} \rightarrow A_2 \rightarrow A}$

</td></tr>
</table>

Step 5C: Quantify the Applicable PRT and MT Requirements for Each Driving Task Component

Procedure

The general model to be applied for quantifying driver task requirements (i.e., required PRT and MT) is **$SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A$.** Driver task requirements are determined for each task as follows.

No TCDs present:

$SD_{HAZ} \rightarrow A$

Apply applicable PRT and MT requirement corresponding to predetermined condition (i.e., SSD, ISD, DSD, or PSD as determined in Step 5A).

TCDs present:

$SD_{TCD} \rightarrow LD_{TCD}$

Drivers should be able to detect a TCD prior to time required to comprehend its message; 2.5 s is desirable, although less time may be adequate (e.g., second, third, etc. in a sequence).

$LD_{TCD} \rightarrow TCD$

LD_{TCD} is the "legibility distance" or approach distance at which a traffic control device message is comprehended. A detailed discussion in the following paragraphs addresses the **LD_{TCD}** for signs. In the case of pavement markings, **LD_{TCD}** is the advance distance at which the marking is visually recognized.

The **LD_{TCD}** for a sign is the distance at which its legend is read or its symbol message is comprehended. PRT requirements for signs consist of reading times for the message legend and symbol as follows (Smiley, 2000):

Reading Time =
1*(number of symbols) +
0.5*(number of words and numbers) [s]

The minimum reading time is 1 s. For messages exceeding four words, the sign requires multiple glances; the driver must look back to the road and at the sign again. Therefore, for every additional four words and numbers, or every two symbols, an additional 0.75 s should be added to the reading time.

TCDs present (continued):

This segment must be sufficient in length to accommodate the reading time noted above. However, its length is constrained by letter height (i.e., limited to 40 ft for every inch of letter height). For example, a 4-in. letter-height sign must be read within a distance of $4 \times 40 = 160$ ft. On a 40 mi/h (58.8 ft/s) roadway, the driver is limited to a maximum of 160/58.8 or 2.7 s to read the sign. Moreover, the traffic engineer must consider that the driver can not be expected to fixate on the sign.

Considering the driver's alerted state after reading the sign, *decision time* (i.e., time to make a choice and initiate a maneuver if required) can range from 1 s for commonplace maneuvers (e.g., stop, reduce speed) to 2.5 s or more when confronted with a complex highway geometric situation.

$LD_{TCD} \rightarrow TCD \rightarrow A$

While the required MT may be initiated prior to passing the TCD, it must be completed in the above-noted segment. MT values associated with designed sight distance considerations are treated in Chapter 5. Additional literature sources of extensive maneuver time data are available (Lerner, Steinberg, Huey, and Hanscom, 1999).

References:

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Smiley, A. (2000). Sign design principles. *Ontario Traffic Manual.* Ottawa, Canada: Ontario Ministry of Transportation.

Step 5D: Assess the Adequacy of the Available Sight Distance Components

Procedure	
Case 1: Direct line of sight to hazard; no traffic control **$SD_{HAZ} \rightarrow A$** Does the subsection length **$SD_{HAZ} \rightarrow A$** allow sufficient time for the driver to perform any required hazard avoidance maneuver? **Case 2:** Intervening traffic control device (i.e., warning of hazard) **$SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A$** Does the subsection length, **$SD_{TCD} \rightarrow LD_{TCD}$** allow sufficient time (minimum 1.5 s) for the driver to detect the traffic control device? Does the subsection length, **$SD_{TCD} \rightarrow TCD$** allow sufficient time for the driver to detect and read the traffic control device? Does the subsection length, **$TCD \rightarrow A$** allow sufficient time for the driver to perform any required hazard avoidance maneuver?	**Case 3:** Intervening, distracting hazard at **A_2** within sight line of first hazard at **A_1**. **$SD_{HAZ1} \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1$** Does then subsection length **$SD_{HAZ1} \rightarrow A_1$** allow sufficient time for the driver to process and respond to the intervening distraction (i.e., apply DSD criteria) and perform any required hazard avoidance maneuver? **Case 4:** Intervening traffic control device and distracting hazard **A_2** within sight line of first hazard **A_1**. **$SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1$** Does the subsection length, **$SD_{TCD} \rightarrow LD_{TCD}$** allow sufficient time (2.5 s desirable; minimum 1.0 to 1.5 s) for the driver to detect the traffic control device? Does the subsection length, **$SD_{TCD} \rightarrow TCD$** allow sufficient time for the driver to detect and read the traffic control device? Does the subsection length, **$TCD \rightarrow A_1$** allow sufficient time for the driver to process and respond to the intervening distraction (i.e., apply DSD criteria) and perform any required hazard avoidance maneuver?

Step 6: Develop Engineering Strategies for Improvement of Sight Distance Deficiencies

In this final step, the practitioner recommends improvement (e.g., traffic control device applications or minor design modifications) to correct deficiencies.

Step 6A: Apply Traffic Engineering and Highway Design Principles to Component Sight Distance Deficiencies

Procedure	Product/Application
Case 1: Direct line of sight to hazard; no traffic control $\mathbf{SD_{HAZ} \rightarrow A}$ Available sight distance to hazard, $\mathbf{SD_{HAZ}}$, is less than required based on Step 5B results.	Add warning traffic control device, increasing warning distance as shown in Case 2 below.
Case 2: Intervening traffic control device (i.e., warning of hazard) $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$ Total available sight distance less than the required sight distance from Step 5C.	If $\mathbf{LD_{TCD} \rightarrow TCD}$ is inadequate (i.e., information overload): • Apply "information spreading" by adding more devices, each with less information • Increase legibility distance (e.g., by increasing letter size) If $\mathbf{LD_{TCD} \rightarrow TCD \rightarrow A}$ is inadequate: • Increase warning distance, $\mathbf{SD_{TCD} \rightarrow LD_{TCD}}$, via improving the TCD's legibility distance • Apply larger device, increase letter size • In DSD condition, add conspicuity device (e.g., flashing beacon) or consider ITS application. If $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD}$ is inadequate: • Reduce information load on existing TCDs • Apply additional TCDs (e.g., delineation devices, advance supplemental devices) to convey essential information.
Case 3: $\mathbf{SD_{HAZ1} \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$ Available sight distance to hazard, $\mathbf{SD_{HAZ}}$, is less than required based on Step 5B results.	Add warning traffic control device, achieving increased warning distance.
Case 4: $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow SD_{HAZ2} \rightarrow A_2 \rightarrow A_1}$ Total available sight distance less than the required sight distance from Step 5C.	Apply combination of Case 2 solutions noted above.

Example Application: Sight Distance Diagnostic Procedure

The example driving situation consists of a 55-mi/h, two-lane rural roadway that approaches a 35-mi/h curve followed by a stop-controlled intersection. The intersection approach is to a main highway, which requires application of destination guide signing.

Driver requirements in this situation are as follows:

1. Reduce speed from 55 to 35 mi/h to negotiate curve
2. Process traffic control device information related to intersection (e.g., destination name sign)
3. Stop for intersection

Step 1: Collect Field Data and Prepare Site Diagram

The labeled site diagram is shown in Figure 22-5.

Step 2: Conduct Preliminary Engineering Analyses

This example requires a sight distance analysis to two separate potential hazards. The first is a 35-mi/h curve that requires slowing from 55 mi/h; and the second is an intersection that is heavily signed with a stop sign and two guide signs, containing multiple route shields, symbols, and destination names. The approach roadways to each hazard point are separately treated as follows: (1) curve approach and (2) signed intersection approach.

Curve Approach Segment

Steps 2A through 2D: Examine Site with Respect to AASHTO Design and DSD Criteria. For the purpose of this example, it is assumed that geometrics conform to AASHTO and that DSD criteria (e.g., visually cluttered environmental conditions) do not apply.

Step 2E: Examine Traffic Control Devices for Compliance with the MUTCD. The MUTCD specifies requirements for warning signs. The curve warning sign in the example is a "W1-2, Horizontal Alignment Sign" with a 35-mi/h advisory speed plate. Section 2C-05 of the MUTCD specifies an advance placement guideline for warning signs. Given the requirement to slow from 55 to 35 mi/h, the minimum recommended distance in Table 2C-4 (located on page 2C-5) is 138 ft (FHWA, 2003).

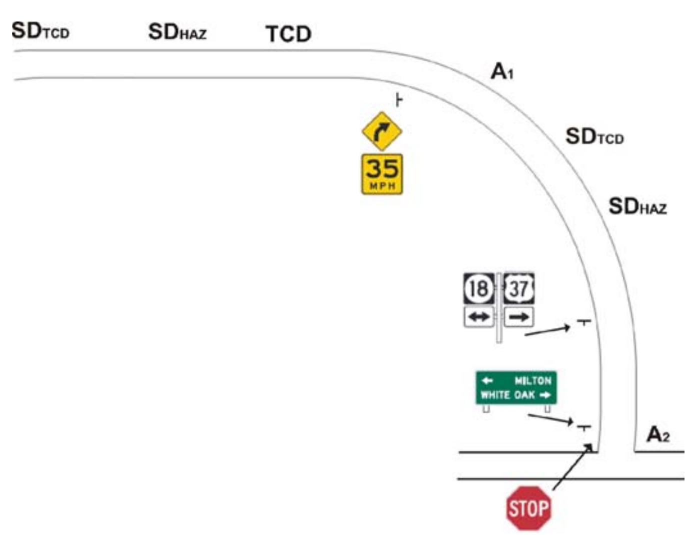

Figure 22-5. Example site diagram.

Signed Intersection Approach Segment

Steps 2A through 2D: Examine Site with Respect to AASHTO Design and DSD Criteria. For the purpose of this example, it is assumed that geometrics conform to AASHTO and that DSD criteria (e.g., visually cluttered environmental conditions) do not apply.

Step 2E: Examine Traffic Control Devices for Compliance with the MUTCD. This segment is a stop-controlled intersection approach containing signs to multiple routes and destinations.

The MUTCD provides requirements for guide signs on conventional roads. Signs in the example consist of a "directional assembly" with destination name signs and route shields. Required advance distances and spacing of these signs is given in Figure 2D-2 (FHWA, 2003). Typically, when a series of guide signs is placed sequentially along the approach to an intersection there is a 100- to 200-ft separation between the first two signs. The minimum spacing between signs is 100 ft, which is intended to enable drivers to read the entire message on both signs. Section 2D.06 requires 6-in. letter heights for a 35-mi/h roadway (FHWA, 2003).

Specifications for stop sign size and placement are contained in Chapter 2A of the MUTCD. As shown in Figure 2A-2, the stop sign should be set back a minimum of 12 ft from the intersection. The recommended letter height is 8 in. (FHWA, 2003).

Step 3: Apply Crash Data

Not conducted as part of this example.

Step 4: Establish Roadway Segments

This example requires a sight distance analysis to two separate potential hazards. The first is slowing from 55 mi/h to 35 mi/h, the posted curve advisory speed; and the second is a stop-controlled approach to an intersection containing signs to multiple routes and destinations. As above, the approach roadways are discussed separately.

Curve Approach Segment. The roadway segment requiring the driver to slow from 55 mi/h to 35-mi/h is labeled in accordance with Steps 4A and 4B and is shown below. The two sight distance driver response scenarios follow:

- **Case 1,** direct line of sight to hazard (i.e., 55-mi/h speed zone to 35-mi/h curve): $\mathbf{SD_{HAZ} \rightarrow A}$
- **Case 2,** intervening traffic control device (i.e., 35-mi/h advisory speed sign warning of hazard): $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$

This roadway is diagrammed in Figure 22-6.

Signed Intersection Approach Segment. On this roadway section, motorists traveling at 35-mi/h are confronted with a stop-controlled intersection and two guide signs containing destination names and route shields. Because sight distance to the intersection is limited by a curve on the approach, a sight distance analysis is critical. The component section diagram is labeled in accordance with Steps 4A and 4B and shown below. The sight distance driver response scenarios follow:

Figure 22-6. Curve approach segment diagram.

- **Case 1,** direct line of sight to hazard (i.e., 35-mi/h speed zone to intersection): $\mathbf{SD_{HAZ} \rightarrow A}$
- **Case 2:** Three intervening traffic control devices
  - A route shield assembly:
    $\mathbf{SD_{TCD1} \rightarrow LD_{TCD1} \rightarrow TCD_1 \rightarrow A}$
  - A destination name sign:
    $\mathbf{SD_{TCD2} \rightarrow LD_{TCD2} \rightarrow TCD_2 \rightarrow A}$
  - A stop sign:
    $\mathbf{SD_{TCD3} \rightarrow LD_{TCD3} \rightarrow TCD_3 \rightarrow A}$

This roadway segment is diagrammed in Figure 22-7.

Step 5: Analyze Component Driving Task Requirements

Curve Approach Segment. The roadway section, requiring the driver to slow from a 55-mi/h speed zone to a 35-mi/h curve, considers sight distance to the curve and legibility distance requirements posed by the advisory speed sign.

Step 5A: Determine the Relevant Design Sight Distance Application. The applicable design sight distance is *slowing sight distance*—the required distance for a driver to observe the curve ahead and adjust speed accordingly. In the event that certain visual noise conditions or other factors are present that would render the curve difficult to perceive, then the practitioner must consider applicable DSD criteria (discussed in Chapter 5). Where a traffic control device is present, driver information-processing time is required to observe and comprehend the sign as well as slow to a safe curve negotiation speed. In the current example (i.e., a rural uncluttered environment), DSD criteria are not applied.

Step 5B: Determine the Driving Task Requirements. Considering the two possibilities (i.e., Case 1 in which the driver observes the curve ahead without seeing the sign, and in Case 2 whereby the driver observes and comprehends the sign), the requirements for each are as follows:

- **Case 1,** direct line of sight to hazard (i.e., 55-mi/h speed zone to 35-mi/h curve):
  $\mathbf{SD_{HAZ} \rightarrow A}$
  The sight distance requirement in this case is simply that the driver observes the curve ahead and slows to a safe speed.
- **Case 2,** intervening traffic control device (i.e., 35-mi/h advisory speed sign warning of hazard):
  $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$
  The sight distance requirement in this case is that the driver observes the sign, comprehends the sign message, and slows to a safe speed.

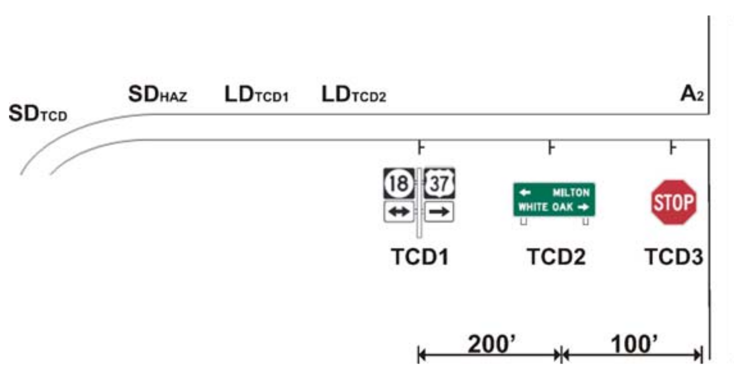

Figure 22-7. Intersection approach segment diagram.

Step 5C: Quantify the Applicable PRT and MT Requirements for Each Driving Task

- **Case 1,** direct line of sight to hazard (i.e., 55-mi/h speed zone to 35-mi/h curve):
  $SD_{HAZ} \rightarrow A$

  Because DSD does not apply (determined previously), the design PRT value of 2.5 s is applied; thus the PRT component of sight distance is 202 ft (i.e., 2.5 s times 80.85 ft/s). The MT requirement (4.0 s) is derived from the need to slow from 55 mi/h to 35 mi/h at a comfortable deceleration level (i.e., .23*g*), which requires 261 ft. Thus the total PRT and MT sight distance requirement is 463 ft.

  The comfortable deceleration level is derived from Exhibit 2-25 of AASHTO (2004). (For safety purposes, wet weather deceleration is considered.) However, AASHTO (2004) acknowledges that its deceleration data may be outdated and that more rapid (albeit uncomfortable) decelerations are common. A typical such deceleration is .35*g* (Knipling et al., 1993), resulting in an MT of 2.6 s. It is also known that most reasonably alert drivers are able to initiate braking within a PRT of 1.6 s (Chapter 5). Applying these performance parameters to slowing from 55 to 35 mi/h, the total required PRT distance is 129 ft plus 172 ft MT distance, or 301 ft.

  It is unlikely that the need to slow to 35 mi/h would be visually evident from an advance distance of either 301 or 463 ft. Therefore, the critical sight distance consideration is based on the application of the speed advisory sign.

- **Case 2,** intervening traffic control device (i.e., 35-mi/h advisory speed sign warning of hazard):
  $SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A$

  In this case the driver needs to detect the sign, read the sign, and decelerate to the safe curve speed. A critical requirement for sight in advance of a sign (i.e., allowing time to comprehend the sign's message) is known as *legibility distance.* There is a considerable body of knowledge regarding sign legibility distance requirements (Smiley, 2000).

  For simple warning signs, the MUTCD specifies an advance placement guideline, which includes "an appropriate legibility distance" of 175 ft for word legend signs or 100 ft for symbol signs. The MUTCD sign placement requirement to allow for slowing from 55 to 35 mi/h is 350 ft.

  Driver requirements imposed by the MUTCD rule in this case are as follows: Given that 2.0 s are needed to detect and comprehend (e.g., minimum 1.0 s for detection plus 1.0 s for symbol comprehension) the simple warning sign message prior to the initiation of slowing, the deceleration requirement would be .32 *g* or approximately the equivalent slowing rate of skidding on wet pavement. In this example the required PRT and MT distances would be 161 and 189 ft respectively, for a total of 350 ft.

  For signs with complex messages (i.e., sets of destination names or symbols in combination with symbols), message comprehension may require significantly more legibility distance. The next example illustrates such a situation.

Signed Intersection Approach Segment. On this roadway section, motorists traveling at 35 mi/h are confronted with a stop-controlled intersection and two guide signs containing destination names and route shields. Because sight distance to the intersection is limited by a curve on the approach, a sight distance analysis is critical.

Step 5A: Determine the Relevant Design Sight Distance Application. As the driver approaches a stop-controlled intersection, there must be sufficient available stopping sight distance (Chapter 5) to enable stopping at the stop line. (While negotiation of the intersection involves the application of intersection sight distance, the current example is limited to approaching the intersection.)

Step 5B: Determine the Driving Task Requirements. Considering the two possibilities (i.e., Case 1 in which the driver proceeds to the intersection ahead while ignoring the signs, and Case 2 whereby the driver observes and comprehends the intermediate signs), the requirements are as follows:

- **Case 1,** direct line of sight to hazard (i.e., 35-mi/h speed zone to intersection):
  $\mathbf{SD_{HAZ} \rightarrow A}$

  The sight distance requirement (to accommodate travel time) in this case is simply that the driver observes the intersection ahead and safely slows to a stop.
- **Case 2,** three intervening traffic control devices, i.e.:
  – A route shield assembly:
  $\mathbf{SD_{TCD1} \rightarrow LD_{TCD1} \rightarrow TCD_1 \rightarrow A}$
  – A destination name sign:
  $\mathbf{SD_{TCD2} \rightarrow LD_{TCD2} \rightarrow TCD_2 \rightarrow A}$
  – A stop sign:
  $\mathbf{SD_{TCD3} \rightarrow LD_{TCD3} \rightarrow TCD_3 \rightarrow A}$

  $\mathbf{TCD_1}$ is a route shield assembly bearing two route designations; $\mathbf{TCD_2}$ is a destination guide sign with two destination names and directional arrows; and $\mathbf{TCD_3}$ is a stop sign.

  The sight distance requirement in this case is that the driver detects and comprehends the signs and slows to a safe stop at the stop line.

Step 5C: Quantify the Applicable PRT and MT Requirements for Each Driving Task

- **Case 1,** direct line of sight to hazard (i.e., speed reduction from 35 mi/h to stop at the stop line):
  $\mathbf{SD_{HAZ} \rightarrow A}$

  The design *stopping sight distance* does not accommodate information-processing requirements of the intervening guide signs. The AASHTO design SSD value (AASHTO, 2004) for a 35-mi/h approach is the range of 225 to 250 ft, which accounts for both the PRT and MT tasks.

  However, this 225- to 250-ft sight distance would barely accommodate the physical placement of the two guide sign assemblies that are shown in the Figure 22-7. Moreover, the information-processing load imposed by the signs requires significant attention in terms of sight distance requirements. Therefore the Case 2 condition is treated below.

- **Case 2,** intervening traffic control device (i.e., guide signs):
  $\mathbf{SD_{TCD} \rightarrow LD_{TCD} \rightarrow TCD \rightarrow A}$

  The general model (above) entails the following considerations. First, there must be sufficient sight distance so that the sign is detected prior to the time required to comprehend the sign's message, thus application of the $\mathbf{SD_{TCD}}$ term. This advance distance is not specified in the MUTCD. Nevertheless, 2.5 s is desirable for this sign detection task, although less time may be adequate as motorists who are looking for signs are generally aware of the expected position in their field of view. The more essential approach sight distance to a traffic control device is that required to comprehend its message.

  $\mathbf{LD_{TCD}}$ refers to legibility distance—the approach distance at which a TCD legend is read or its symbol message is comprehended. The legibility distance of a legend sign is determined by multiplying a legibility index (i.e., the distance at which a given unit of letter height is readable) by the letter height. The applicable legibility index values are shown in Table 22-2. For example, the legibility distance typically associated with 6-in. letter height is 240 ft (40 times 6).

Table 22-2. Legibility index.

Metric	US Customary
4.8 meters/ centimeter of letter height	40 feet/ inch of letter height

The legibility distance of symbol signs has been researched in a laboratory study (Dewar, Kline, Schieber & Swanson, 1994) and found to significantly exceed that of legend signs (despite the high degree of variability in the study data). For example, the mean legibility distance for the right curve arrow symbol was determined to be 283 m (with a standard deviation of 68 m). Considering that a 55-mi/h approach allowing a 2.5-s advance sight distance and 1.0-s reading time would consume only 86 m, pure symbol signs are not expected to result in an information-processing problem.

The required PRT for this example roadway segment consists of three components: detecting the signs, comprehending the sign messages, and detecting the intersection. Each is separately discussed.

Sign Detection. Upon a driver's detection of the first sign, the second and third signs would require minimal detection time. The recommended detection time for the first sign is 2.5 s; however, the second two signs are likely to be detected much more rapidly. "Alerted" PRT responses are known to occur in as little as 1.0 to 1.5 s. Moreover, signs can be quickly detected as drivers know where to look for signs and typically scan toward expected sign locations. Therefore, a conservative sign detection PRT for the example roadway segment is (2.5 + 1.5 + 1.5) or 5.5 s.

Sign Comprehension. Sign comprehension consists of reading the sign plus making the resultant decision (e.g., right or left turn in response to the sign's information). The PRT requirement (Smiley, 2000) is based on sign-response reading and decision time, for which general rules are noted in Table 22-3.

Table 22-3. General rules for sign comprehension PRT requirements.

Comprehension Task	PRT Requirements
Reading	Time requirements for reading the sign are 0.5 s for each word or number, or 1 s per symbol, with 1 s as a minimum for total reading time. In the event of the sign's containing redundant information, the reading time computation should be limited to critical words. The suggested formula for estimating sign reading time is: Reading time = 1(number of symbols) + 0.5(number of words and numbers). For messages exceeding four words, the sign requires multiple glances, which means the driver must look back to the road and at the sign again. Therefore, for every additional four words and numbers, or every two symbols, an additional 0.75 s should be added to the reading time. When the driver is sufficiently close to see a sign at an angle, the sign is not visible for the last 0.5 s. Therefore, 0.5 s should be added to the required reading time. An exception applies to signs requiring a maneuver before the sign is reached, as no further reading is required.
Deciding	Considering the driver's alerted state having read the sign, decision time can range from 1 s for commonplace maneuvers (e.g., stop or reduce speed) to 2.5 s or more when confronted with a complex highway geometric situation.

The first guide sign assembly contains two numbers and two symbols, requiring 3.0 s of reading time; the second contains two designation names and two symbols, also requiring 3.0 s; and the third is a simple and familiar one-word regulatory sign, requiring 1 s. Thus the total sign reading time is 7.0 s. This estimate is highly conservative, as drivers would likely scan the guide signs seeking only a particular name or route number; however, it is necessary to provide sufficient information-processing sight as some drivers may need the entire set of information. An additional 3.0 s is considered for decision time responses to the three signs. Thus the total comprehension time for the three signs is 10 s.

Intersection Detection Distance. As noted above under the Case 1 ($\mathbf{SD_{HAZ} \rightarrow A}$) discussion, the stopping sight distance requirement considers a 2.5-s PRT.

A summary of the above-noted PRT requirements, if separately considered, is shown in Table 22-4. The sum of PRT requirements would apply to a serial task process. However, a realistic assessment of PRT requirements considers that many of the tasks in Table 22-4 are concurrent. For example, stop sign comprehension would not logically entail a separate process of perceiving the intersection, thus conceivably reducing the total PRT by 2.5 s. In addition, following a driver's 2.5-s detection of the initial sign, the subsequent two signs would likely be detected with a minimum detection time (e.g., 1.0 s rather than 1.5 s), thus conceivably reducing the total PRT by another 1.0 s. Therefore, subtracting 3.5 s from the serial total of 19.5 s, the estimated PRT requirement becomes 16.0 s.

The MT requirement (i.e., to slow from 35 mi/h to a stop at the specified AASHTO g-force) calculates to 4.7 s over a distance of 120 ft. The extent to which the deceleration process would occur concurrently with the various sign-response tasks is uncertain. However, it is logical (and best serves liability concerns) to allow time for comprehension of all signs prior to the initiation of the slowing response.

Therefore, the overall sight distance requirement is approximately 16.0 s of sign information processing at 35 mi/h (51.45 ft/s) or 823 ft, plus the 120-ft deceleration distance, for a total of 943 ft. (Actual requirements will reflect real-world conditions. If possible, data should be collected at the relevant sites.)

A final consideration is the necessity that drivers have sufficient time to comprehend a sign's message during the interval when the message is discernable. Therefore, an essential sight distance diagnostic step is to compare the available sign legibility distance (i.e., available reading distance) with distance traveled during reading PRT (i.e., required reading distance and decision time). Table 22-5 contrasts the distance traveled during PRT with the legibility distance. While the guide signs in this example accommodate both reading time and associated decision time, the decision component of PRT can obviously be accomplished after the driver passes the sign.

Table 22-4. Summary of PRT requirements.

Driving Task	PRT Requirement (s)
Perceive initial guide sign	2.5
Perceive next three signs @ 1.5 s/sign	4.5
Comprehend initial guide sign	4.0
Comprehend second guide sign	4.0
Comprehend stop sign	2.0
Perceive intersection	2.5
Total	**19.5**

Table 22-5. Contrast of distance traveled during PRT with legibility distance.

Sign	Legibility Distance (ft)	PRT Distance (ft)
1. 6-in. letters: 2 Numbers + 2 Symbols	240	231
2. 6-in. letters: 2 Numbers + 2 Symbols	240	231
3. 8-in. letters: 1 Word	320	51

Step 6: Develop Engineering Strategies for Improvement of Sight Distance Deficiencies

Not conducted as part of this example.

CHAPTER 23

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CHAPTER 24

Glossary

Forthcoming

CHAPTER 25

Index

Forthcoming

CHAPTER 26

Abbreviations*

AASHTO	American Association of State Highway and Transportation Officials
ABS	Anti-Lock Braking System
ADA	Americans with Disabilities Act
APS	Accessible Pedestrian Signals
ASD	Available Sight Distance
cd	Candela
CMS	Changeable Message Signs
DSD	Decision Sight Distance
FARS	Fatal Accident Reporting System
FHWA	Federal Highway Administration
HCM	*Highway Capacity Manual*
HFG	*Human Factors Guidelines for Road Systems*
HSM	*Highway Safety Manual*
ISD	Intersection Sight Distance
ITE	Institute of Transportation Engineers
LD	Legibility Distance
LED	Light-Emitting Diode
MMI	Most Meaningful Information
MT	Maneuver Time
MUTCD	*Manual on Uniform Traffic Control Devices*
NCHRP	National Cooperative Highway Research Program
NHTSA	National Highway Traffic Safety Administration
PRT	Perception-Reaction Time
PSD	Passing Sight Distance
RT	Reaction Time
RTOR	Right Turn on Red
SD	Sight Distance
SLIDE	Simplified Location of Information Deficiencies
SSD	Stopping Sight Distance
TCD	Traffic Control Device
vph	Vehicles per Hour

*Covers Chapters 1 through 5, 10, 11, 13, and 22.

CHAPTER 27

Equations

Forthcoming

Abbreviations and acronyms used without definitions in TRB publications:

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	Air Transport Association
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
FHWA	Federal Highway Administration
FMCSA	Federal Motor Carrier Safety Administration
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
ISTEA	Intermodal Surface Transportation Efficiency Act of 1991
ITE	Institute of Transportation Engineers
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
SAE	Society of Automotive Engineers
SAFETEA-LU	Safe, Accountable, Flexible, Efficient Transportation Equity Act: A Legacy for Users (2005)
TCRP	Transit Cooperative Research Program
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