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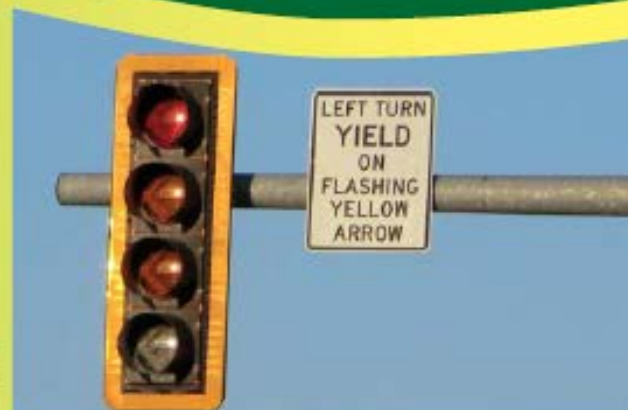
Exam Preview:

1. Traffic signals play a prominent role in achieving safer performance at intersections. Research has shown that the proper installation and operation of traffic signals can reduce the severity of crashes. in 2009, ____% of all crashes and ____% of all fatalities and injury collisions occurred at signalized intersections
 - a. 21 & 24
 - b. 22 & 24
 - c. 24 & 21
 - d. 21 & 24
2. Practitioners should adopt an integrated, systems view founded on ____ of the interactions among intersection design, traffic control, environmental factors, and road users.
 - a. direct integration
 - b. human factors principles
 - c. automatic controls
 - d. passive factors
3. At the most basic level, signalized intersections sequence the right-of-way between intersecting streams of road users.
 - a. True
 - b. False
4. Designing facilities that cannot be used by people with disabilities constitutes illegal discrimination under the ADA.
 - a. True
 - b. False

5. Drivers do not dwell on any target for long; studies indicate that most drivers become uncomfortable if they cannot look back at the roadway at least every ____ seconds.
 - a. 1
 - b. 2
 - c. 4
 - d. 6
6. According to the FHWA Highway Design Handbook for Older Drivers and Pedestrians, 2/3 of fatal crashes involving drivers 80 or older took place at intersections.
 - a. True
 - b. False
7. Red light running may occur due to poor engineering, distraction, inattention, or willful disregard. Those who deliberately violate red lights tend to be younger, male, less likely to use seat belts, have poorer driving records, and drive smaller and older vehicles.
 - a. True
 - b. False
8. Pedestrian safety must be a particular concern at signalized intersections, particularly those with a high volume of motorized vehicles. Speed plays a major role in motorist pedestrian collisions, particularly fatalities; a pedestrian struck at 40 mph has an ____ % chance of being killed.
 - a. 70
 - b. 75
 - c. 80
 - d. 85
9. Horizontal & Vertical Alignment - Drivers' or bicyclists' expectations on approaches to an intersection could be violated under if approach grades to an intersection of greater than 2 %, and mitigation efforts should be considered.
 - a. True
 - b. False
10. The basic principle behind intersection lighting is that the amount of light on the intersection should be proportional to the classification of the intersecting streets and equal to the sum of the values used for each separate street.
 - a. True
 - b. False

Signalized Intersections Informational Guide

Second Edition



FHWA Safety Program

PART I - FUNDAMENTALS



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Signalized Intersections

Informational Guide

Second Edition

Publication No. FHWA-SA-13-027

July 2013



U.S. Department of Transportation
Federal Highway Administration

FOREWORD

This report, now in its Second Edition, complements the American Association of State Highway and Transportation Officials (AASHTO) Strategic Highway Safety Plan (SHSP) efforts to develop guidance on enhancing the safety of unsignalized and signalized intersections. The overarching goal is to reduce the number of traffic related deaths that occur on highways and streets in the United States. This guide is an introductory document that contains methods for evaluating the safety and operations of signalized intersections and tools to remedy deficiencies. The treatments in this guide range from low-cost measures such as improvements to signal timing or signing and markings, to high-cost measures such as intersection widening or reconstruction. Topics covered include fundamental principles of user needs and human factors, multimodal accommodations (emphasizing pedestrians and bicyclists), elements of geometric design, and traffic safety design and operation; safety, maintenance and operations practices; and a wide variety of treatments, techniques and strategies to address existing or anticipated problems at multiple levels, including corridor, approach and individual movement treatments. Each recommended treatment includes a discussion of safety performance, operations, multimodal issues, and physical and economic factors that the practitioner should consider. While some treatments may be better suited to high-volume intersections, most of the treatments are applicable for lower volume intersections and would be worthy of systemic implementation. Every attempt has been made to reflect the latest research and documentation on available treatments and best practices in use by jurisdictions across the United States at the time of publication. Since the scope of this guide is necessarily limited, additional resources and references are highlighted for the student, practitioner, researcher, or decision maker who endeavors to learn more about a particular subject.

An electronic version of this document can be downloaded from the Federal Highway Administration, Office of Safety website at <http://safety.fhwa.dot.gov/>. A hard copy may be requested by contacting the National Highway Institute, 1310 North Courthouse Road, Suite 300, Arlington, VA 22201; telephone (703) 235-0500; fax (703) 235-0593.



Michael Griffith
Director
Office of Safety Technologies

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SI* (MODERN METRIC) CONVERSION				
FACTORS APPROXIMATE CONVERSIONS TO SI UNITS				
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
AREA				
in ²	square inches	645.2	square millimeters	mm ²
ft ²	square feet	0.093	square meters	m ²
yd ²	square yard	0.836	square meters	m ²
ac	acres	0.405	hectares	ha
mi ²	square miles	2.59	square kilometers	km ²
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft ³	cubic feet	0.028	cubic meters	m ³
yd ³	cubic yards	0.765	cubic meters	m ³
NOTE: volumes greater than 1000 L shall be shown in m ³				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
ILLUMINATION				
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m ²	cd/m ²
FORCE and PRESSURE or STRESS				
lbf	poundforce	4.45	newtons	N
lbf/in ²	poundforce per square inch	6.89	kilopascals	kPa
APPROXIMATE CONVERSIONS FROM SI UNITS				
SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
AREA				
mm ²	square millimeters	0.0016	square inches	in ²
m ²	square meters	10.764	square feet	ft ²
m ²	square meters	1.195	square yards	yd ²
ha	hectares	2.47	acres	ac
km ²	square kilometers	0.386	square miles	mi ²
VOLUME				
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m ³	cubic meters	35.314	cubic feet	ft ³
m ³	cubic meters	1.307	cubic yards	yd ³
MASS				
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
TEMPERATURE (exact degrees)				
°C	Celsius	1.8C+32	Fahrenheit	°F
ILLUMINATION				
lx	lux	0.0929	foot-candles	fc
cd/m ²	candela/m ²	0.2919	foot-Lamberts	fl
FORCE and PRESSURE or STRESS				
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in ²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.

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CHAPTER 1

INTRODUCTION

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References to be used throughout the Guide include:

- TRB *Highway Capacity Manual* (2010)
- FHWA *Manual on Uniform Traffic Control Devices* (2009)
- AASHTO *A Policy on Geometric Design of Highways and Streets* (2011)
- AASHTO *Highway Safety Manual* (2010)
- TRB NCHRP Report 500 series
- FHWA *Alternative Intersections and Interchanges Informational Report* (2010)
- U.S. Access Board *Draft Public Rights-of-Way Accessibility Guidelines* (2011)
- U.S. Access Board *ADAAG Requirements for Detectable Warnings* (2008)
- U.S. Access Board *ADA Standards for Accessible Design* (2010)
- FHWA *Traffic Signal Timing Manual* (2008)
- FHWA *Traffic Detector Handbook* (2006)
- ITE *Traffic Control Devices Handbook* (2011)
- IESNA *American National Standard Practice for Roadway Lighting* (2005)

1.0 INTRODUCTION

This document serves as an introduction to and guide for evaluating the safety, design, and operations of signalized intersections. It also provides tools to deliver better balanced solutions for all users. The treatments in this guide range from low-cost measures such as improvements to signal timing and signing, to high-cost measures such as intersection reconstruction or grade separation. While some treatments apply only to higher volume intersections, much of this guide is applicable to signalized intersections of all volume levels.

The guide takes a holistic approach to signalized intersections and considers the safety and operational implications of a particular treatment on all system users (e.g., motorists, pedestrians, bicyclists, and transit users). When applying operational or safety treatments, it is often necessary to consider the impact one will have on the other. This guide will introduce the user to these trade-offs and their respective considerations.

Practitioners will find the tools and information necessary to make insightful intersection assessments and to understand the impacts of potential improvement measures. The information in this guide is based on the latest research available and includes examples of novel treatments as well as best practices in use by jurisdictions across the United States and other countries. Additional resources and references are mentioned for the practitioner who wishes to learn more about a particular subject.

This guide does not replicate or replace traditional traffic engineering documents such as the *Manual on Uniform Traffic Control Devices* (MUTCD),⁽¹⁾ the *Highway Capacity Manual* (HCM) 2010⁽²⁾ or the American Association of State Highway and Transportation Officials' (AASHTO) *A Policy on Geometric Design of Highways and Streets*,⁽³⁾ nor is it intended to serve as a standard or policy document. Rather, it provides a synthesis of best practices and treatments intended to help practitioners make informed, thoughtful decisions.

1.1 BACKGROUND

Traffic Signal Basics

Traffic signals are electrically operated traffic control devices that provide indication for roadway users to advance their travels by assigning right-of-way to each approach and movement. Traffic signals are a common form of traffic control used by State and local agencies to address roadway operations and safety issues. They allow the shared use of road space by separating conflicting movements in time and allocating delay, and can be used to enhance the mobility and safety of some movements.

Consider the installation of traffic signals when attempting to obtain any of the following:

- Optimization of travel delay
- Reduction of crash frequency and/or severity
- Prioritization of specific roadway user type or movement (such as pedestrians or left turn movements)
- Accommodation of a new intersection approach or increase in traffic volumes (such as the addition of an approach at a new development)

Analysis of traffic volume data, crash history, roadway geometry, and other field conditions are the determining factors when deciding upon the installation of traffic signals. Planners, designers, and traffic engineers work together to determine if conditions are right for installation. Several safety and mobility factors should be considered as new traffic signal installation is being discussed. Chapter 4C of the MUTCD outlines basic warrants for when installation of a traffic signal may be justified. In addition to the considerations presented in the MUTCD, practitioners should give thought to roadway/intersection geometry and sight distance, driver expectancy, and the locations of other nearby traffic signals when considering the installation of new traffic signals.

When weighing the options for traffic control types at an intersection, consider the following important factors:

- The design and operation of traffic signals will require choosing elements that may lead to trade-offs in safety and mobility.
- It is possible to lower the overall crash severity at intersections with traffic signals, but increase the crash frequency. Table 14-7 of the 2010 Highway Safety Manual illustrates the effects of converting a stop controlled intersection to a signalized intersection.
- There will be ongoing operational costs attributed to the maintenance of signal equipment and costs for electrical power.

Once installed, the traffic engineers and field traffic signal technicians who operate and maintain the traffic signals should regularly perform site visits to:

- Ensure that safety and mobility targets for the intersection are being met, and make adjustments to signal timings, if necessary, to meet the targets;
- Inspect corresponding intersection signing and pavement markings to ensure they properly convey the intended instructions to roadway users;
- Log site visit findings for use when making adjustments or recommendations for change; and
- Communicate traffic signal maintenance and repair needs to field technicians.

Ideally, field traffic signal technicians are qualified to perform maintenance inspections at regular intervals. Repairs are made such that the signal operates safely and efficiently at all times. Technicians are also responsible for the general upkeep and operation of signal equipment located at the intersection.

An agency will identify that a traffic signal needs upgrades, replacement or decommission at some point during its life. Degradation of equipment, new technology, or changing conditions at the site, such as lane additions or the need for alternate phasing, may necessitate an upgrade or full replacement. In some instances, the traffic signal may be completely removed if traffic patterns cease to warrant its use.

Traffic Operations: Safety and Mobility

Traffic signals play a prominent role in achieving safer performance at intersections. Research has shown that the proper installation and operation of traffic signals can reduce the severity of crashes. However, unnecessary or inappropriately designed signals can adversely affect traffic, safety, and mobility. Care in their placement, design, and operation is essential.

In some cases, the dual objectives of mobility and safety will conflict. To meet increasing and changing demands, one element may need to be sacrificed to achieve improvements in the other. In all cases, it is important to understand the degree to which traffic signals are providing mobility and safety for all roadway users.

Assuring the efficient operation of the traffic signal is becoming an increasingly important issue as agencies attempt to maximize vehicle roadway capacity to serve the growing demand for travel, while maintaining a high level of safety.

Reducing crashes should always be one of the objectives whenever the design or operational characteristics of a signalized intersection are modified. As described by the Federal Highway Administration (FHWA), the “mission is not simply to improve mobility and productivity, but to ensure that improved mobility and productivity come with improved safety.”⁽⁴⁾

Exhibit 1-1 shows that in 2009, 21 percent of all crashes and 24 percent of all fatalities and injury collisions occurred at signalized intersections.

Exhibit 1-1. Summary of motor vehicle crashes related to junction and severity in the United States during 2009.

	Total Crashes		Fatalities/Injuries	
	Number	Percent	Number	Percent
Non-Intersection Crashes	3,295,000	60	841,027	54
Signalized Intersection Crashes	1,158,000	21	372,299	24
Non-Signalized Intersection Crashes	1,052,000	19	332,471	22
Total	5,505,000	100	1,547,797	100

Source: Adapted from table 29 of *Traffic Safety Facts 2009*.⁽⁵⁾

How a Traffic Signal Works

Traffic signals are designed to allow for the safe and efficient passage of road users when demand exists. Types of traffic signal operation include pre-timed, semi-actuated, fully-actuated, hybrid, adaptive, or traffic responsive. Pre-timed signals give right-of-way to movements based on a predetermined allocation of time. Semi-actuated signals use various detection methods to identify roadway users on the minor approaches, while fully-actuated signals recognize users on all approaches. Chapter 5 discusses each of these methods in further detail.

In addition to the signal heads seen by the road users, signalized intersections may include additional components, such as loop detectors and video detection equipment. The following paragraphs provide information related to each component.



Exhibit 1-2. Vehicle detection by inductive loop (left) and video (right)
(Source: Left: South Carolina DOT / Right: Jeff Shaw, FHWA)

Detection.

Semi- and fully actuated signals use various methods to detect road users. Detection methods for motorists include in-pavement loop detectors or sensors (Exhibit 1-2 (left)) and cameras mounted to signal poles (Exhibit 1-2 (right)). Detection methods for pedestrians and bicyclists include push buttons and weight sensors.

Traffic signal controller.

Each detection method sends vehicle presence information to a traffic signal controller. The controller acts as the “brain” of the traffic signal, changing signal indications based on programmed instructions. The controller will determine when the indication for the approach will change and how much time will be given to each movement. A controller is shown in Exhibit 1-3.

Traffic control algorithms determine the priority and length of time of each approach movement. These algorithms are tailored to the needs of each intersection, based on historical user demand, crash history, and other roadway network considerations.

Signal heads.

Traffic signal heads inform roadway users of when their movement can proceed through the intersection. Signal heads for motorists and bicyclists are usually mounted on mast arms or span wires above the travel lane, and are sometimes repeated on the signal pole. Pedestrian signal heads are often installed on the traffic signal pole, or independently on separate poles depending on the intersection design. Signal heads vary in configuration, shape, and size depending on the movement for which they are used.



Exhibit 1-3. Inside a signal controller cabinet.
Photo Credit: Missouri DOT

Types of Signalized Intersections

In their most common form, signalized intersections have indications for users on each intersection approach. Exhibit 1-4, below, shows a basic signalized intersection with four vehicle approaches and two pedestrian approaches.

In addition to signalizing intersections, it may be necessary to consider the use of pedestrian signals at locations along a corridor with high concentrations of pedestrians. This type of traffic control can be used at signalized intersections with the addition of pedestrian push-buttons and signal heads, or at non-signalized locations that have high volumes of pedestrians crossing. This guide also provides direction on the use of treatments such as the Pedestrian Hybrid Beacon. Pedestrian signals are discussed in more detail in Chapter 5.

1.2 PERFORMANCE MEASUREMENT AND ASSET MANAGEMENT

Agencies face the challenge of providing outstanding customer service with limited resources. Performance measures allow practitioners to assess the effectiveness of a signalized intersection or corridor. These measures can help agencies more effectively allocate resources. Travel performance criteria include: stopped delay, travel speed, arrivals on red, and excessive queuing. Safety performance criteria include crash frequency, crash types, and severity. Traffic signal maintenance data could be categorized according to time of day or types of repair. Over time, practitioners and agencies can refine or adjust these measures.

The practitioner should review this data to assess problem areas to correct. Other information that may be needed includes comments from the practitioner's annual signal timing reviews and annual preventive maintenance program. Examples of questions that may arise from such a review:

- What intersections require monthly visits to fix?
- What types of repetitive repairs are being conducted over a wide number of intersections?
- Are phasing (or other) changes necessary to reduce the number of crashes?

Practitioners should create queries that identify problematic intersections. These queries can also identify global intersection treatments that reduce systematic problems. For example, an agency could choose to install uninterrupted power supply (UPS) units for frequent power outages. The following information can be utilized to monitor performance:

- Detection failures by type of device.
- Outages due to power surges and outages.
- Customer complaints and complements.
- Emergency personnel comments.
- Frequent equipment hits by errant vehicles.
- Damage by weather events.
- Intermittent issues.
- Number of red failures.

Reviews of these measures should involve traffic engineers, technicians, and operations personnel to create a culture of continuous improvement.

1.3 SCOPE OF THE GUIDE

This guide addresses safety and operation for all users of signalized intersections, including motorists, pedestrians, bicyclists, and transit riders. This guide addresses Americans with Disabilities Act (ADA) requirements and provides guidelines for considering older drivers.

Roundabouts and other alternative intersection designs are not addressed directly in this document; for more information, please refer to *Roundabouts: An Informational Guide, Second Edition* ⁽⁶⁾ and the FHWA *Alternative Intersections/Interchanges Informational Report*. ⁽⁵⁵⁾

1.4 AUDIENCE FOR THIS GUIDE

This guide is intended for planners, designers, traffic engineers, operations analysts, and signal technicians who perform or want to perform one or more of the following functions as they pertain to signalized intersections:

- Evaluate substantive safety performance experienced by system users.
- Evaluate operational performance experienced by system users.
- Identify treatments that could address a particular operational or safety deficiency.
- Understand fundamental user needs, geometric design elements, or signal timing and traffic design elements.
- Understand the impacts and tradeoffs of a particular intersection treatment.

It is envisioned that this guide will be used by signal technicians, design and traffic engineers, planners, and decision-makers who:

- Wish to be introduced to basic and intermediate traffic signal concepts.
- Are involved with the planning, design, and operation of signalized intersections, particularly those with high volumes.
- Are involved with the identification of potential treatments.
- Make decisions regarding the implementation of treatments at those intersections.

1.5 ORGANIZATION OF THE GUIDE

This guide is arranged in three parts:

- Part I: Fundamentals.
- Part II: Project Process and Analysis Methods.
- Part III: Treatments.

Part I (Chapters 2-5) provides key background information on three topic areas: user needs, data collection, signal warrants, geometric design, and traffic design and illumination. These chapters provide a foundation of knowledge of signalized intersections useful as a learning tool for entry-level engineers and as a refresher for more experienced engineers. Parts II and III reference the information in these chapters.

Part II (Chapters 6-7) describes project process and analysis methods. These chapters outline the steps that should be carried out and the tools to consider for evaluating the safety and operational performance of an intersection and determining geometric and timing needs.



Exhibit 1-4. Signalized intersection with four approaches.
Source: FHWA

Part III (Chapters 8-11) provides a description of treatments that can be applied to mitigate a known safety or operational deficiency. The treatments are organized by chapter, based on the intersection element. Within each chapter, the treatments are grouped by a particular user type (e.g., pedestrian treatments) or are grouped to reflect a particular condition (e.g., signal head visibility).

Exhibit 1-5 depicts the organization of the guide.

Exhibit 1-5. Organization of the guide.

Part	Chapter	Title
	1	Introduction
Part I: Fundamentals	2	User Needs
	3	Data Collection and Warrants
	4	Geometric Design
	5	Traffic Design and Illumination
Part II: Project Process and Analysis Methods	6	Safety Analysis Methods
	7	Operational Analysis Methods
Part III: Treatments	8	System-Wide Treatments
	9	Intersection-Wide Treatments
	10	Approach Treatments
	11	Individual Movement Treatments

Exhibit 1-6 provides a list of the treatments discussed in Part III. Each treatment includes a description, a photo or diagram where available, and a summary of the treatment's applicability. In addition, these sections identify the following:

- Key design elements;
- Operational and safety impacts;
- Impacts on other modes;
- Socioeconomic and physical impacts; and
- Education, enforcement, and maintenance issues.

The treatments in Exhibit 1-6 represent some, but not all, possible treatments.

Exhibit 1-6. List of intersection treatments discussed in this guide.

Treatment Type	Treatments	
System-Wide Treatments (Chapter 8)	<ul style="list-style-type: none"> • Median treatments • Access management 	<ul style="list-style-type: none"> • Provide signal coordination • Provide signal preemption/priority
Intersection-Wide Treatments (Chapter 9)	<ul style="list-style-type: none"> • Reduce curb radius • Provide curb extensions • Modify stop line location • Improve pedestrian signal display • Modify pedestrian signal phasing • Grade separate pedestrian movements • High visibility crosswalks 	<ul style="list-style-type: none"> • Provide bicycle box (experimental) • Provide bike lanes • Relocate transit stop • Change signal control from pre-timed to actuated • Modify change and clearance intervals • Modify cycle length • Remove late night/early morning flash • Provide or upgrade illumination • Convert signalized intersection to a roundabout or all-way stop control.
Approach Treatments (Chapter 10)	<ul style="list-style-type: none"> • Convert to over-the-road signal heads • Add supplemental signal heads • Increase size of signal heads • Increase number of signal heads • Provide backplates 	<ul style="list-style-type: none"> • Provide advance warning • Improve lane use and street name signing • Reduce operating speed • Improve pavement surface • Improve cross section • Remove obstacles from clear zone • Improve sight lines • Provide dilemma zone protection • Provide red light camera enforcement
Individual Movement Treatments (Chapter 11)	<ul style="list-style-type: none"> • Add single left-turn lane • Add multiple left-turn lane • Add channelizing islands • Add single right-turn lane • Provide double right-turn lanes 	<ul style="list-style-type: none"> • Restrict turns, U-turns • Provide auxiliary through lane • Delineate through path • Provide reversible lane • Provide variable lane use assignments

Part I

Fundamentals

Part I discusses the fundamentals of signalized intersections as they relate to Human Factors (Chapter 2), Data Collection and Warrants (Chapter 3), Geometric Design (Chapter 4), and Traffic Signal Design and Illumination (Chapter 5). These chapters are intended for use by entry-level engineers and other users of the guide who seek broad-level information on the technical aspects of signalized intersections. The information provides a background for the chapters in Part II and Part III.

CHAPTER 2

Human Factors

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2.0 HUMAN FACTORS

This chapter describes road user needs at and around signalized intersections. The description is based on three assumptions:

- Practitioners should adopt an integrated, systems view founded on human factors principles of the interactions among intersection design, traffic control, environmental factors, and road users.
- The road user—motorist, bicyclist, and pedestrian—is the operative element in the system; decisions affecting user performance taken at any point in the roadway life cycle often involve tradeoffs involving one or more road user types.
- Practitioners need to fully understand and quantify intersection operations and safety performance in the pursuit of informed and balanced decision-making.

A discussion of user needs requires an understanding of human factors principles for all intersection users. This chapter provides an introduction to human factors research, followed by a description of user needs for motorists, pedestrians, and bicyclists. The chapter concludes with a discussion of applying human factors principles to the planning, design, and operation of signalized intersections.

2.1 OVERVIEW OF HUMAN FACTORS

Human factors research deals with human physical, perceptual, and cognitive abilities and characteristics and how they affect our interactions with tools, machines, and surroundings. The goals of human factors analysis in road transportation are to:

- Explain, as fully as is possible, the information needs, processing abilities, and characteristics of road users.
- Study the human-machine-situational interactions that occur.
- Capitalize on this knowledge through improvements in engineering design and operations.

At signalized intersections, the application of human factors principles to the problems of safety and mobility requires a systems-oriented and human-centered approach. A systems approach helps capture the dynamic interaction between the road user and the roadway environment. It acknowledges that no one element can be analyzed and understood in isolation. A human-centered approach recognizes road users as the operative element within the system—the decision-makers—and focuses the engineering effort on optimizing their performance.

Human factors analysis, particularly as it relates to any element of the transportation system (including signalized intersections), includes the following tasks:

- Ensuring road users are presented with tasks that are within their respective capabilities under a broad range of circumstances.
- Designing facilities accessible to and usable by all road users.
- Anticipating how road users may react to specific situations to increase the likelihood of predictable, timely, accurate, and correct responses, thus avoiding situations that violate road users' expectations.
- Designing and applying conspicuous, legible, comprehensible, and credible traffic control devices that provide sufficient time to respond in an appropriate manner.
- Understanding how geometric design properties of width, enclosure, slope, and deflection affect users and contribute to behaviors such as speeding, yielding, and gap acceptance.

Signalized intersections serve a variety of road users, chiefly motorists, bicyclists, and pedestrians. Each road user group includes multiple user types. For example, motorists include passenger car, commercial truck, bus, and motorcycle operators. Bicyclists include recreational and commuting bicyclists with a wide range of ages and abilities. Pedestrians include all age groups (children, adults, elderly). Some pedestrians may also have cognitive, mobility, or vision impairments. Practitioners should account for road users' abilities and characteristics when designing an intersection.

At the most basic level, signalized intersections sequence the right-of-way between intersecting streams of road users. These intersections thus serve multiple functions: they allow motorists to access new streets and change directions in travel; they are junctions for bike routes; and they provide a primary connection to and from activity centers for pedestrians. Signalized intersections are often located on primary routes leading to commercial activities, which may involve motor carriers and other heavy vehicles. Intersections also serve as public right-of-way and include space for public utilities such as power and communication lines; water, sewage, and storm drainage pipes; and traffic signs and signal equipment.

Each category of road user has different needs when traversing an intersection. Motorists and bicyclists must detect the intersection on the approach, assess its relevance from a navigational perspective, respond to the applicable traffic controls, and negotiate the intersection. In a similar manner, pedestrians must identify the crossing location, maneuver to and position themselves accordingly at the crossing, activate a crossing device, and respond appropriately to the traffic controls. All users must remain vigilant for potential conflicts with other road users.

The Americans with Disabilities Act (ADA) of 1990 prohibits discrimination and ensures equal opportunity and access for persons with disabilities.⁽⁷⁾ Designing facilities that cannot be used by people with disabilities constitutes illegal discrimination under the ADA. Designing safe and usable facilities demands an understanding that persons with disabilities have varying abilities, use a variety of adaptive devices, such as motorized and non-motorized wheelchairs, guide dogs, walkers, and walking canes, and may have multiple impairments. ADA standards were updated in 2012 and serve as guidelines for the design and management of accessible facilities, not public rights-of-way.

The *Proposed Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way*⁽⁵⁴⁾ was developed specifically for pedestrian facilities in the public right-of-way. It addresses conditions and constraints in the public right-of-way. The requirements in the proposed guidelines make allowances for typical roadway geometry and permit flexibility in alterations to existing facilities where existing physical constraints make it impractical to fully comply with new construction requirements. The proposed guidelines also include requirements for elements and facilities that exist only in the public right-of-way, such as pedestrian signals and roundabouts.⁽⁸⁾ While these guidelines are proposed and not legal standards, they do represent best practice. In some cases, State and local agencies have adopted policies and standards equal to or more stringent than those presented in the proposed guidelines.

Road users can only process a limited amount of information. The pace at which vehicle drivers and bicyclists encounter information increases with travel speed. The number of choices facing drivers and bicyclists at any one time should be minimized. The information presented should be concise, complete, explicit, and located sufficiently in advance of the choice point to allow for a comfortable response.

2.1.1 Positive Guidance

In the 1980s, FHWA's Office of Human Factors developed a series of documents advocating the explicit application of human factors-based knowledge in the design of roadways and in the design, selection, and application of information presentations targeted at vehicle users.⁽⁹⁾

Termed *positive guidance*, the concept focuses on understanding and making allowances for how road users—primarily motorists—acquire, interpret, and apply information in the driving task. Key positive guidance concepts are *driver expectation*, *expectancy violation*, *primacy*, and *road user error*.

Positive guidance places the driving task within the framework of a road environment viewed as an information system, where the driver is the operative element. The roadway, with its formal and informal sources of information, becomes the input. The vehicle, controlled by the driver, becomes the conduit for output. The driving task itself is subdivided into three performance levels: control, guidance, and navigation, each oriented in decreasing order of primacy and increasing order of complexity.

Positive guidance is founded on a simple concept: providing drivers with all of the information they need, in a format they can readily read, interpret and apply, and in sufficient time to react appropriately, reduces the chances of driver error and improves relative safety. Uniformity in the design and context of application of information presentations is a key component of positive guidance. Information presentations must work within the roadway information system to reinforce correct driver expectations and restructure incorrect driver expectations. They must provide the information necessary to support rapid decision-making while minimizing the potential for driver error.

Strict interpretation of the positive guidance concept implies telling the driver what he or she needs to know and nothing else. In practical application, positive guidance suggests competition for driver attention by information irrelevant to driving-related tasks can exceed drivers' information-processing limitations. This may have a negative impact on traffic safety.

This road user-based approach to information presentation is the foundation of state-of-the-art information presentation policies, standards and guidelines, including FHWA's MUTCD.⁽¹⁾ However, a growing body of research suggests that redundancy in message delivery systems may in fact improve the efficiency, safety, and/or usability of a facility. For example, pedestrians tend to begin their crossing more quickly if an audible prompt accompanies the visible pedestrian signal indication. However, there is always a risk that some users will miss or be unable to receive information that relies on only one sense (e.g., sight).

2.1.2 Roadway Safety Fundamentals

In the past, roads were considered to be “safe” if they were designed, built, operated, and maintained in accordance with nominal standards of the day. These standards were usually based on empirical data or long-standing practice. Collisions were viewed as an unavoidable outcome of the need for mobility and the inevitability of human error. When human errors resulted in collisions, the fault was perceived to lie with the road user, rather than with the road.

The approach to roadway safety has since evolved. In the explicit consideration of roadway safety, safety itself is now recognized to be a relative measure, with no road open to traffic being considered completely “safe”—only “more safe” or “less safe” relative to a particular benchmark, as defined by one or more safety measures. While the concept of “road user error” remains, it is now understood that errors and the collisions that result do not just “happen,” they are “caused,” and the roadway environment sometimes plays a role in that causation.

In the Institute for Transportation Engineers (ITE) *Traffic Safety Toolbox: A Primer on Traffic Safety*, Hauer refers to *nominal* safety as compliance with standards, warrants, guidelines and sanctioned design procedures, and *substantive* safety as the expected crash frequency and severity for a highway or roadway.⁽¹⁰⁾ More recently, AASHTO published the Highway Safety Manual (HSM). The HSM provides tools to practitioners to conduct quantitative safety, allowing

for safety to be quantitatively evaluated alongside other transportation performance measures such as traffic operations, environmental impacts, and construction costs in project planning and development decision-making.⁽¹¹⁾

By addressing the environmental and situational elements that contribute to the occurrence of driver error, the forgiving roadway seeks to break the chain of causation between the erroneous decisions and/or actions and their undesirable outcomes (e.g., crashes). The forgiving roadway concept is largely information driven. It is predicated on meeting the expectations of road users—motorists, bicyclists, and pedestrians—and assuring that they get needed information when it is required, in an explicit and usable format and in sufficient time to react. Implicit in the forgiving roadway approach is that the information-processing capabilities of users must at no time be overtaxed by either an overabundance of potentially relevant information or by the additive presence of information not immediately relevant to the task of negotiating the roadway.

2.2 INTERSECTION USERS

Knowing the performance capabilities and behavioral characteristics of road users is essential for designing and operating safe and efficient signalized intersections. All road users deal with human factors, no matter how they use the road. For example, older drivers, older pedestrians, and people with visual disabilities all frequently share the characteristic of longer perception-reaction times. The following section discusses human factors issues common to all road users, followed by a discussion of issues specific to motorists, bicyclists, and pedestrians.

2.2.1 Human Factors Common to All Road Users

The task of traveling on the roadway system, whether by motor vehicle, bicycle, or foot, primarily involves searching for, finding, understanding, and applying information, as well as reacting to the appearance of unanticipated information. Once found and understood, the relevance of this information must be assessed and decisions and actions taken in response. This activity is cyclic, often occurring many times per second in complex, demanding environments. The capabilities of human vision, information processing, and memory all affect a road user's ability to use an intersection, and these may affect the likelihood of user error. The following sections discuss each of these factors.

Human Vision

Road users who are not visually impaired receive most of their information visually. The human visual field is large; however, the area of accurate vision is quite small. Drivers, for example, tend to scan a fairly narrow visual field ahead of them. Drivers do not dwell on any target for long; studies indicate that most drivers become uncomfortable if they cannot look back at the roadway at least every two seconds.⁽¹²⁾ This means that information searches and the reading of long messages are carried out during a series of glances rather than with one long look. Complex or cluttered backgrounds, such as those shown in Exhibits 2-1 and 2-2, make individual pieces of information more difficult to identify and can make the driving task more difficult. Looking at irrelevant information when it is not appropriate to do so may cause drivers to overlook relevant information or fail to accurately monitor a control or guidance task. This is of particular concern in areas of high workload, at decision points, and at locations where there is a high potential for conflict (e.g., intersections and crosswalks).



Exhibit 2-1. Signs confused with background information.



Exhibit 2-2. Example of sign clutter.

Information Processing and Memory

Road users perform best under moderate levels of demand. Information overload or underload tends to degrade performance. Consider the example of driving. The presentation of information in circumstances of low driving-task demand is commonly assumed to avert boredom; however, this assumption is untested.⁽¹³⁾ During periods of high task demand, however, it is known that the duration of drivers' glances at signs become shorter, as more time is needed to accommodate control and guidance tasks and less is available for reading signs. Extra effort should be made to limit information presentations to those immediately relevant to the driving task where circumstances of high workload are apt to occur.

Humans have limited short-term memory. Only a small percentage of what they see is actually remembered, including information presentations viewed while driving, bicycling, or walking. Long-term memory is made up of experiences ingrained through repetition. These are the source of our expectations, which play a strong role in the performance of all road users. Information about an upcoming condition or hazard should be proximate to its location, or repeated at intervals for emphasis.

In addition to expectations, road users recognize and use patterns to anticipate and prepare for situations similar to those experienced before. When things turn out as expected, performance is often rapid and error-free. When expectations are violated, surprise results, and new information must be gathered so the user can rethink a response. Adherence to uniform principles of information presentation in the design and application of traffic control devices—and managing the overall information load placed on road users—is vital to ensure that the users get the information they need when they need it, in a form that they can recognize and understand and in time to perceive and react to it in an appropriate manner.

User Error

Information presentations must be conspicuous, legible, readable at a glance, and explicit as to their meaning. A study cited in the NCHRP 600 Human Factors Guidelines⁽¹⁵³⁾ refers to an increase in both the number of glances and duration of each glance as the length of a message increases, while the retention of the information significantly decreases for messages longer than eight characters. Uniformity and consistency are paramount. For example, drivers must receive the same clues and information in similar situations so that their expectations will be consistent with reality, or their expectations will be restructured accordingly. The presentations must be located in advance to provide time to react, and they must be spaced—both from each other and from other competing sources of information—so as not to confuse or overload the road user.

Drivers in particular often have difficulties following through the sequence of driving tasks, which leads to driving errors. The most common driving errors include improper lookout (faulty visual surveillance), inattention, false assumption, excessive speed, improper maneuvers, improper evasive action, and internal distraction.⁽¹⁴⁾

The risk of user error tends to increase when needed information:

- **Is missing or incomplete.**
- **Is difficult to locate, read, or interpret.**
- **Lacks credibility.**
- **Leads to false expectations.**
- **Provides insufficient time for decision and appropriate action.**

Bicyclists can also have similar difficulties. These errors often result from:

- Inadequate input for the task at hand (e.g., night time travel, poor sight distance, inconspicuous traffic control devices, complex intersection layouts, insufficient advance signing).
- Uncommon events (e.g., violations by other road users, emergency vehicles traveling through red light).
- Inappropriate inputs (e.g., extraneous or conflicting signage).
- The shedding of important information when overloaded.
- Stress, frustration, inexperience, fatigue, intoxication.
- Imperfect decision-making.

In summary, the engineer should be aware of road users and their needs and limitations with regard to signalized intersections. Information displayed in advance of and at the intersection needs to be consistent, timely, legible, and relevant. Awareness of how human factors play a role in the task of using the intersection will go a long way toward reducing error and the collisions this may cause.

Age

Age and experience have a significant effect on the ability of drivers, bicyclists, and pedestrians to use an intersection. For example, young drivers have a quicker perception and reaction time yet often lack the judgment to perceive something as being hazardous, something only experience can teach a driver. In contrast, older drivers have the experience yet may lack the perception and reaction time.⁽¹⁵⁾

According to the FHWA *Highway Design Handbook for Older Drivers and Pedestrians*, half of fatal crashes involving drivers 80 or older took place at intersections.⁽¹⁵⁾ This document also points to a large body of evidence showing higher crash involvement among older drivers, particularly with crash types that require complex speed-distance judgment under time constraints, such as a left-turn against oncoming traffic. As shown in Exhibit 2-3, fatal crash involvement is much higher at signalized intersections for drivers less than 20 years old and more than 70 years old.

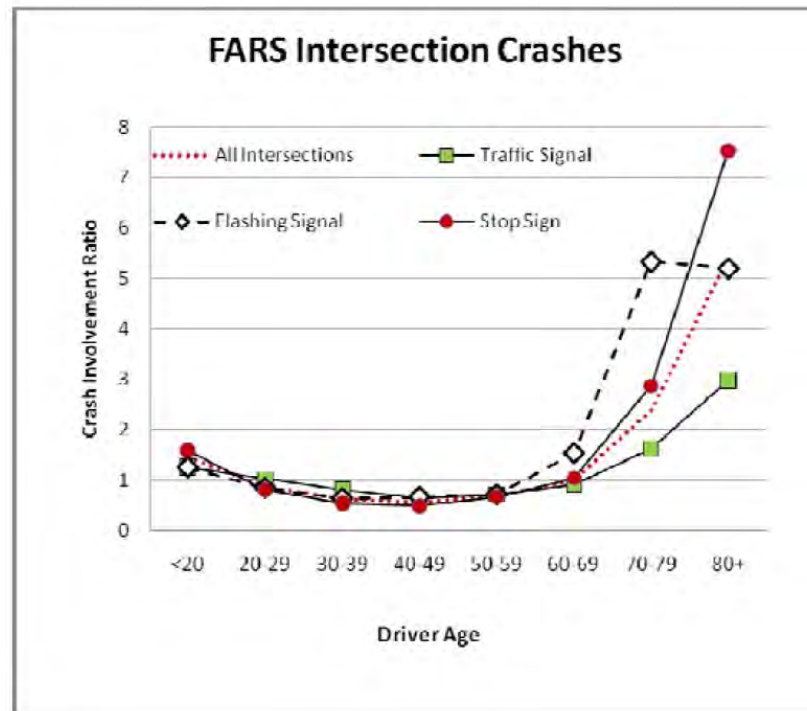


Exhibit 2-3. Fatal two-vehicle intersection crashes by traffic control device and driver age
Source: NHTSA, *Intersection Crashes among Drivers in Their 60s, 70s, and 80s*. 2011.

As one ages, specific functions related to the driving task may deteriorate, such as vision, depth perception, hearing, sensation, and cognitive and motor abilities. Decreased peripheral vision and a decreased range of motion in an older person's neck may limit their ability to attend to a traffic signal while searching for a gap in traffic when making a left turn. Sorting out visual distractions at intersections can be difficult. Cognitive changes require that older drivers need more time to recognize hazards and respond. It would also appear that driving situations involving complex speed-distance judgments under time constraints, as found at many signalized intersections, are problematic for older drivers and pedestrians.

The following specific tasks were reported as being problematic for older road users:

- Reading street signs.
- Driving through an intersection.
- Finding the beginning of a left-turn lane at an intersection.
- Judging a gap in oncoming traffic to make a left turn or cross the street (both as drivers and pedestrians).
- Following pavement markings.
- Responding to traffic signals.

Young drivers aged 16 to 24 have a higher risk (2.5 times) of being involved in a collision compared to other drivers.⁽¹⁶⁾ Young pedestrians (i.e., pedestrians under the age of 12) also have a higher risk of being in a collision. These younger road users may:

- Have difficulty judging speed, distance, and reaction time.
- Tend to concentrate on near objects and other vehicles.
- Miss important information.
- Have a poor perception of how hazardous a situation can become
- Fix their eyes on an object for longer periods.
- Have difficulty integrating information.
- Be easily distracted by unrelated events (e.g. cell phone use, texting, and using GPS).
- Underestimate their risk of being in a collision.
- Make less effective driving and crossing decisions.

2.2.2 Motorists

Motorists account for by far the most number of trips taken on roads. There are more than 254 million licensed vehicles in the United States.⁽¹⁷⁾ Traffic engineers have traditionally sought to design and operate intersections with a typical driver in mind, trying to best accommodate their needs in terms of their ability to perceive, react, and safely navigate through an intersection. This being so, bicyclists and pedestrians are often at a disadvantage at many intersections.

Traffic engineers must be conscious of the need to design for a range of human characteristics and responses. Specific subgroups of drivers may have an elevated risk of being involved in a collision (e.g., teenage drivers, older drivers, and aggressive drivers).

Most drivers traveling through signalized intersections will be operating passenger vehicles. These may be cars, minivans, pickups, or sport utility vehicles (SUVs). A total of 6,763 people died in intersection-related motor vehicle crashes in 2010. These deaths occurred in 2,415 crashes involving 4,471 motor vehicles.⁽¹⁸⁾ However, commercial vehicles (tractor-trailers, single-unit trucks, and cargo vans) account for more than their share of fatal collisions, based on fatal crash rates per mile.⁽¹⁹⁾ These vehicles need to be properly accommodated at intersections.

Vehicle acceleration from a stationary position, braking distances required, safe execution of a left or right turn, and provision of adequate storage in turning lanes are important items to consider.

Exhibit 2-4 identifies general characteristics of vehicle types, and Exhibits 2-5 and 2-6 show the frequency of fatalities and injuries by mode, respectively.

Exhibit 2-4. Estimated number of registered vehicles by type, 2010

Vehicle Type	Number of Registered Vehicles	Percent of Total
Light duty vehicle, short wheel base	190,202,782	76
Motorcycle *	8,212,267	3
Light duty vehicle, long wheel base	40,241,658	16
Truck, single-unit 2-axle 6-tire or more **	8,217,189	3
Truck, combination	2,552,865	1
Bus	846,051	< 1
Total	250,272,812	

*The new category Light duty vehicle, short wheel base replaces the old category Passenger car and includes passenger cars, light trucks, vans and sport utility vehicles with a wheelbase (WB) equal to or less than 121 inches.

**The new category Light duty vehicle, long wheel base replaces Other 2-axle, 4-tire vehicle and includes large passenger cars, vans, pickup trucks, and sport/utility vehicles with wheelbases (WB) larger than 121 inches.

Source: Bureau of Transportation Statistics, 2010.⁽¹⁷⁾

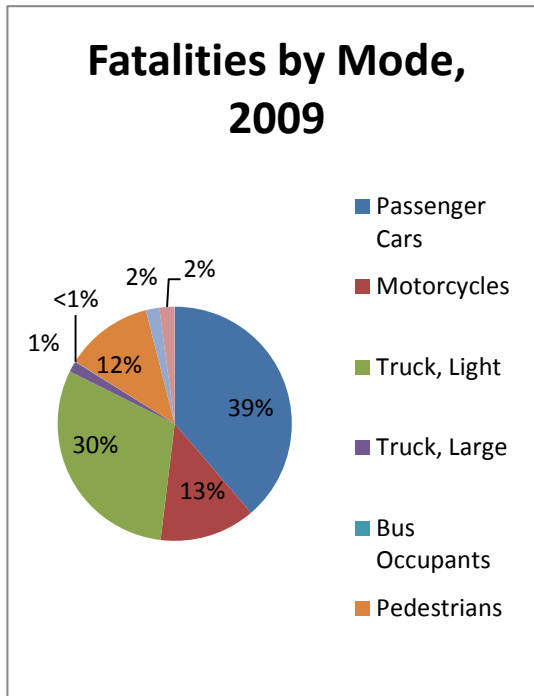


Exhibit 2-5. Fatalities by mode, 2009.

Source: Bureau of Transportation Statistics, 2009.

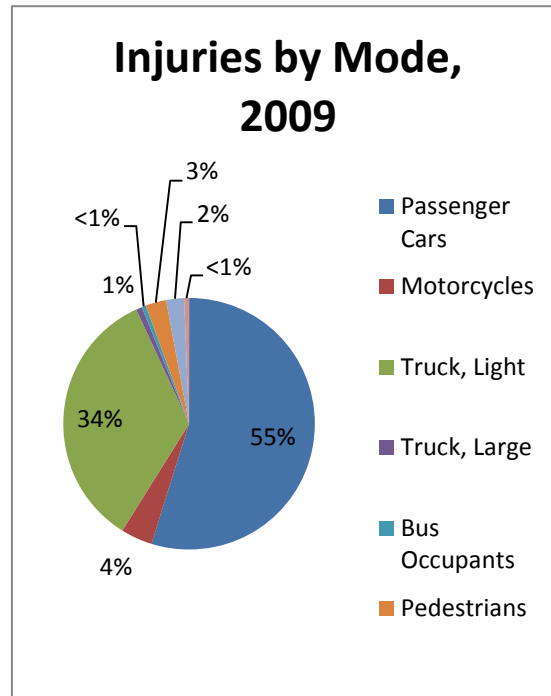


Exhibit 2-6. Injuries by mode, 2009.

Source: Bureau of Transportation Statistics, 2009.

Exhibit 2-7. Proportion of crashes by collision type at four-leg signalized intersections. (Excerpted from Highway Safety Manual (2010), Table 10-6)

Collision Type	Percent
Head on	5
Sideswipe	12
Rear end	43
Angle	27
Ran Off Road	6
Bicycle/Pedestrian	<1
Other	6
TOTAL	100

As shown in Exhibit 2-7, the most frequently occurring collision is a rear-end crash, which represents 43 percent of all reported intersection crashes in the database.

States commonly include strategies targeting signalized intersections in their Strategic Highway Safety Plans (SHSP) spanning engineering, enforcement, and educational opportunities.

The engineering improvements may include:

- Reduce frequency and severity of intersection conflicts through traffic control and operational improvements.
- Reduce frequency and severity of intersection conflicts through geometric improvements.
- Improve sight distance at signalized intersections.
- Improve driver awareness of intersections and signal control.
- Improve driver compliance with traffic control devices.
- Improve access management near signalized intersections.
- Improve drainage in intersection and on approaches.⁽²¹⁾

Red Light Running

One primary cause of collisions at signalized intersections is when a motorist enters an intersection when the red signal is displayed, and as a consequence collides with another motorist, pedestrian, or bicyclist who is legally within the intersection. Red light running may occur due to poor engineering, distraction, inattention, or willful disregard. Those who deliberately violate red lights tend to be younger, male, less likely to use seat belts, have poorer driving records, and drive smaller and older vehicles.

According to the National Highway Traffic Safety Administration's Traffic Safety Facts 2008 Report, there were 762 deaths and 165,000 persons injured by red-light running.⁽²²⁾ A study of Highway Safety Information System (HSIS) data determined that red light runners cause 16 to 20 percent of all collisions at signalized intersections.⁽²³⁾

Countermeasures proposed to address red light running are removal of unwarranted traffic signals, changing the signal timing, improving the visibility of the traffic signal, or enforcement. An example of red light running enforcement cameras is shown in Exhibit 2-8.



Exhibit 2-8. Enforcement cameras, as shown in the photo above, are used at signalized intersections to identify red light runners.

Source: Brian Chandler

Driver Distraction

Despite the complexity of the driving task, drivers commonly engage in other tasks while operating a motor vehicle. While these tasks may seem trivial, they take the attention of the driver away from the task of driving. An estimated 16 percent of fatal crashes in 2009 involved reports of distracted driving.⁽²⁴⁾ Drivers involved in collisions at intersections were more likely to report that they “looked but didn’t see.” According to a 2010 NHTSA report, 32 percent of drivers involved in collisions between 2005 and 2007 were distracted by the following sources:⁽²⁵⁾

- Conversing with a passenger (15.9%).
- Cell phone use/texting (3.4%).
- Other objects within the vehicle (3.2%).
- The actions of other occupants (3.0%).
- Retrieving objects from the floor/seat (2.0%).
- Eating or drinking (1.7%).
- Adjusting the radio/CD player (1.2%).
- Retrieving objects from another location (0.7%).
- Smoking (0.5%).
- Reading map/directions/newspaper (0.4%).
- Adjusting other vehicle controls (0.3%).
- Talking on a CB radio (0.2%).

2.2.3 Bicyclists

Bicycle travel is an important component of any multimodal transportation system. Bicycle travel is healthy, cost effective, energy efficient, and environmentally friendly. Traditionally, the most popular form of bicycle travel is recreational bicycling. Given the increases in traffic congestion over the past few decades, particularly in urban areas, the number of people using bicycles to commute to work is on the rise.⁽²⁶⁾

Bicyclists have unique needs at signalized intersections. Bicyclists are particularly vulnerable because they share the roadway with motorists and are required to follow the same rules of the road, yet they do not possess comparable size, speed, and ability to accelerate as their motor vehicle counterparts. Consequently, roadway characteristics such as grades, lane widths, intersection widths, and lighting conditions influence the safety and operations of bicyclists to a larger degree than they do motor vehicles. External conditions such as inclement weather also significantly affect bicyclists’ performance.

Providing safe, convenient, and well-designed facilities is essential to encourage bicycle use. To accomplish this, planning for bicycle use, whether existing or potential, should be integrated into the overall transportation planning process.⁽²⁶⁾

Providing a safe and attractive environment for bicyclists requires special attention to the types of bicycle users, their characteristics and needs, and factors that influence bicyclist safety.

Bicycle Users

Bicyclists range widely in terms of skills, experience, and preferences. An FHWA report defined the following general categories (A, B, and C) of bicycle user types⁽²⁷⁾:

- “**A**dvanced or experienced riders are generally using their bicycles as they would a motor vehicle. They are riding for convenience and speed and want direct access to destinations with a minimum of detour or delay. They are typically comfortable riding with motor vehicle traffic; however, they need sufficient operating space on the traveled way or shoulder to eliminate the need for either [them] or a passing motor vehicle to shift position.
- “**B**asic or less confident adult riders may also be using their bicycles for transportation purposes, e.g., to get to the store or to visit friends, but prefer to avoid roads with fast and busy motor vehicle traffic unless there is ample roadway width to allow easy overtaking by faster motor vehicles. Thus, basic riders are comfortable riding on neighborhood streets and shared use paths and prefer designated facilities such as bike lanes or wide shoulder lanes on busier streets.
- “**C**hildren, riding on their own or with their parents, may not travel as fast as their adult counterparts but still require access to key destinations in their community, such as schools, convenience stores and recreational facilities. Residential streets with low motor vehicle speeds, linked with shared use paths and busier streets with well-defined pavement markings between bicycle and motor vehicle, can accommodate children without encouraging them to ride in the travel lane of major arterials” (cited on p. 6, reference 22).

Bicyclist Dimensions

Although the physical width of a bicycle is approximately 30 inches, the forward movement of bicyclists requires a minimum operating width of 4 ft and a preferred operating width of 5 ft to accommodate the natural side-to-side movement that varies with speed, wind, and bicyclist proficiency.⁽²⁸⁾ In addition, because most bicyclists ride a distance of 32 to 40 inches from a curb face, this area should be clear of drain inlets, utility covers, and other items that may cause the bicyclist to swerve. Where drain inlets are unavoidable, their drainage slots should not run parallel to the direction of travel, as this can cause a bicyclist to lose control.

Bicycle User Needs

The general objectives for bicycle travel are similar to those for other modes: to get from point A to point B as efficiently as possible on a route that is safe and enjoyable. At the same time, the mode of travel must integrate with other forms of transportation that use the roadway network and not adversely affect other modes or uses.

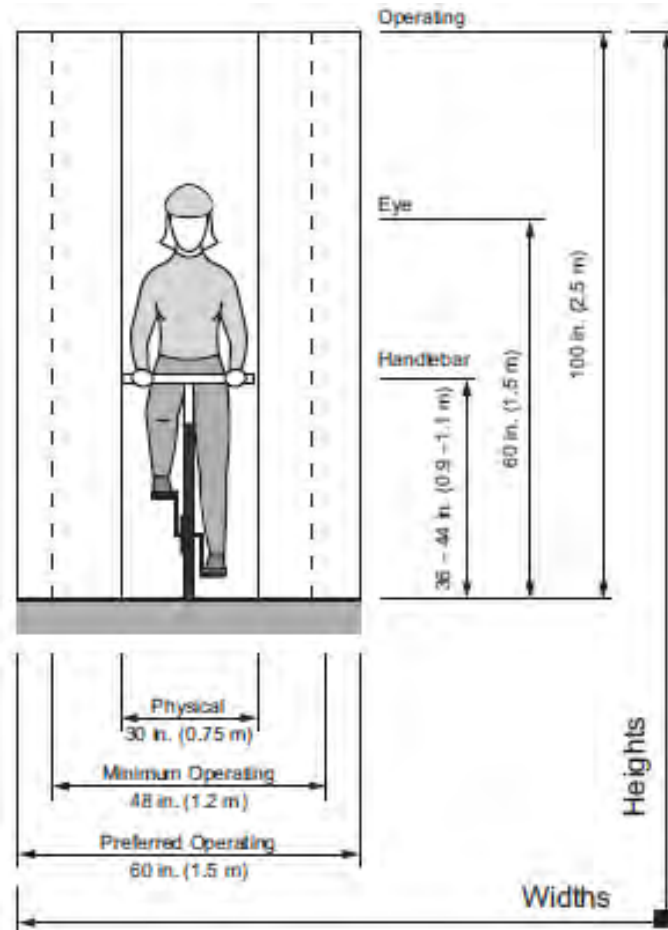


Exhibit 2-9. Typical dimensions of a bicyclist.

Source: AASHTO, *Guide for the Development of Bicycle Facilities*, 4th Edition, 2012.

- **Width** – The minimum operating width of 4 ft, sufficient to accommodate forward movement by most bicyclists, is greater than the physical width momentarily occupied by a rider because of natural side-to-side movement that varies with speed, wind, and bicyclist proficiency. Additional operating width may be needed in some situations, such as on steep grades, and the figure does not include shy distances from parallel objects such as railings, tunnel walls, curbs, or parked cars. In some situations where speed differentials between bicyclists and other road users are relatively small, bicyclists may accept smaller shy distances.
- **Height** – The operating height of 8.3 ft can accommodate an adult bicyclist standing upright on the pedals.⁽²⁶⁾

The Danish Road Directorate identifies key elements to incorporate in the planning of cycling facilities:

- **Accessible and coherent.** The bicycle network should run directly from residential areas to the most important destinations, such as schools, workplaces, and shopping and entertainment centers.
- **Direct and easy.** If the bicycle network is not direct, logical, and easy to use, some bicyclists will choose roads not planned for bicycle traffic.
- **Safe and secure.** Adequate visibility and curve radii should make it possible for bicyclists to travel safely at a minimum of 15 mph. Parked cars, vegetation, barriers, etc. can result

in poor or reduced visibility. Awareness of the presence of bicyclists can be heightened by signing and road marking.

- **Self-explanatory design.** Edge lines, bicycle symbols, colored tracks and lanes, and channelization of traffic make it easy to understand where bicyclists should place themselves. Uniformity over long stretches is an important component.

Other elements that should be considered in the planning and design of bicycle facilities include bike lanes, pavement surface conditions, drainage inlet grates, refuge, and lighting.⁽²⁹⁾

Bicycle Safety

In 2009, 630 bicyclists were killed and 51,000 injured in motor vehicle traffic crashes.^{(30),(31)} Bicyclist deaths accounted for 2 percent of all motor vehicle traffic fatalities and made up 2 percent of all the people injured in traffic crashes during the year. However, many bicycle crashes either do not involve a motor vehicle or go unreported. A study of records at eight hospitals in three States found that 55 percent of bicycle injury events in a roadway did not involve a motor vehicle.⁽³²⁾ In addition, the study found that 40-60 percent of bicycle-motor vehicle crashes were not reported to the official State files.

Bicycle-motor vehicle crashes are a concern at intersections. An FHWA report identified three common crash types that occur at intersections:⁽³³⁾

- Motorist left turn facing the bicyclist.
- Bicyclist left turn in front of a motorist.
- Bicyclist ride-out from a stop sign or flashing red signal.

Exhibit 2-10 presents the typical conflicts for bicyclists at a signalized intersection. As the exhibit shows, bicyclists going straight through a signalized intersection encounter the same conflicts as a motor vehicle (shown in the exhibit as open circles), but also encounter additional conflicts from motor vehicles turning right from the same direction.

Left turns for bicyclists are even more complex and depend on the type of bicyclists. For small- to medium-sized signalized intersections, Category A and some Category B bicyclists will generally choose to take the lane as a motor vehicle, as it is the fastest way through the intersection; the remainder will likely feel more comfortable traveling as a pedestrian, as shown in Exhibit 2-10. As the size of the intersection increases, the difficulty for bicyclists to weave to the left turn lane can be daunting for Category B and even some Category A bicyclists.

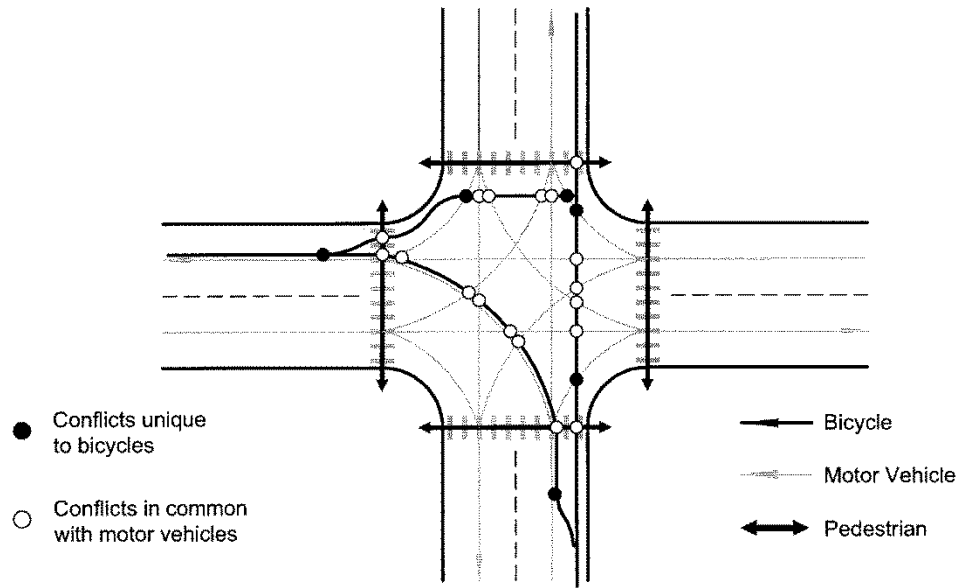


Exhibit 2-10. Bicyclist conflicts at signalized intersections.

From 2005-2009, 1,357 bicycle fatalities occurred at intersections on American roads, according to the Fatality Analysis Reporting System (FARS) database maintained by NHTSA, with 564 of the fatalities occurring at signalized intersections. Intersection-related fatalities are far more common on urban rather than rural roads, and during daylight instead of after dark.

FARS data indicated that 15 percent of all bicycle collisions occur at signalized intersections. In 2010, FARS cited that 30 percent of police-reported collisions between bicyclists and motorists occurring at intersections take place within the pedestrian crosswalk.

2.2.4 Pedestrians

Walking is the oldest and most basic form of transportation. Nearly every trip includes a walking element. According to the *2009 Nationwide Personal Transportation Survey*, 10.4 percent of all daily trips occurred via the walk mode.⁽³⁴⁾ People walk for a variety of reasons: social and recreational activities, trips to school or church, shopping, commuting to and from work, and connecting to or from other modes of transportation. There has also been an increase in non-motorized travel due to successful ongoing public health campaigns that encourage people to walk in lieu of motorized commuter transportation. Activities often concentrate on the corners of intersections where pedestrian streams converge, people interact and socialize, and people wait for crossing opportunities.

The variety of pedestrian users includes persons of all ages, with and without disabilities, persons in wheelchairs, and persons with strollers, freight dollies, luggage, etc.; an example is given in Exhibit 2-11. The design of intersection facilities should accommodate all types of pedestrians, because the user cannot be anticipated.



Exhibit 2-11. Examples of pedestrians of various abilities preparing to cross an intersection.

Pedestrian Dimensions

Research has shown that the ambulatory human body encompasses an ellipse of 18 by 24 inches.⁽³⁵⁾ This dimension, however, does not account for a variety of scenarios, including pedestrians walking side by side; persons using canes, walkers, dog guides, or wheelchairs; persons with shopping carts or baby carriages; and so on. Exhibit 2-12 shows dimensions for various types of pedestrians.

The Americans with Disabilities Act Accessibility Guidelines (ADAAG) specifies a 60-inch square area to allow a wheelchair user to make a 180-degree turn (Exhibit 2-13).⁽³²⁾ For parallel approaches, ADAAG specifies a minimum low-side reach of 9 inches and a maximum high-side reach of 54 inches. For a forward approach, ADAAG specifies a minimum low-reach point of 15 inches and a maximum high-reach point of 48 inches.

Exhibit 2-12. Typical dimensions for a sample of types of pedestrians.

User and Characteristic	Dimension	Affected Intersection Features
Pedestrian (walking)		
Width	1.6 ft	Sidewalk width, crosswalk width
Wheelchair		
Minimum width	2.5 ft	Sidewalk width, crosswalk width
Operating width	3.0 ft	width, ramp landing areas
Person pushing stroller		
Length	5.6 ft	Median island width at crosswalk
Skaters		
Typical operating width	6 ft	Sidewalk width

Source: (6), as adapted from (28).

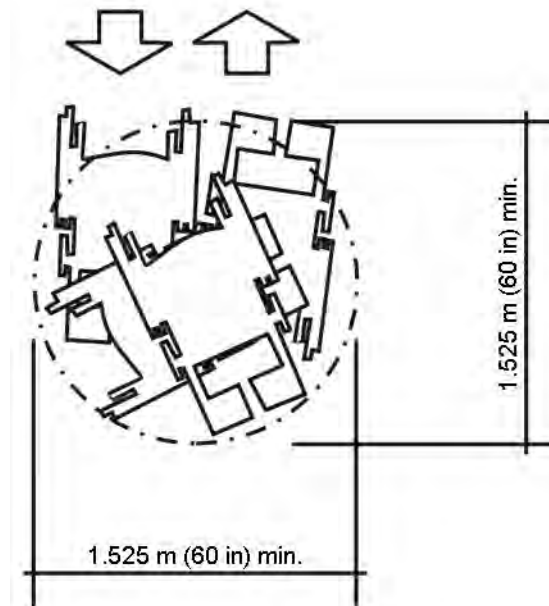


Exhibit 2-13. Typical dimensions for a turning wheelchair.

Source: U.S. Department of Justice, *ADA Standards for Accessible Design (ADAAG)*. 2010.

Pedestrian Characteristics

Pedestrian walking speeds generally range between 2.5 to 6.0 ft/s.⁽³⁾ The MUTCD (Page 497 Sect. 4E.06-07, Paragraph 7) uses a walking speed of 3.5 ft/s for determining crossing times.⁽¹⁾ However, FHWA pedestrian design guidance recommends a lower speed in general to accommodate users who require additional time to cross the roadway, and in particular a lower speed in areas where there are concentrations of children and or elderly persons.^{(37),(38)} The *HCM 2010* indicates that if elderly persons constitute more than 20 percent of the total pedestrians, the average walking speed decreases to 3.0 ft/s.⁽³⁹⁾



Exhibit 2-14. Crosswalks are used by a variety of users with different speed characteristics.

A general rule of thumb indicates that pedestrians at crossings are willing to wait only 30 seconds, at which point they will begin to look for opportunities to cross, regardless of the walk indication and the crossing location.⁽²⁾ Shorter cycle lengths benefit pedestrians, particularly where pedestrians often need to cross two streets at a time to travel in a diagonal direction, as well as drivers, who experience generally shorter delays.

Pedestrian Conflicts

Exhibit 2-15 presents the typical conflicts between pedestrians and motor vehicles at a signalized intersection.

- **Vehicles turning right on red.** Where allowed by law, this conflict occurs most often when the driver of a vehicle turning right on red is looking to the left and does not perform an adequate search for pedestrians approaching from the right and crossing perpendicularly to the vehicle. In addition, the sound of vehicles turning right on red masks audible cues used by blind pedestrians to determine the beginning of the crossing phase.
- **Vehicles turning right on green.** This conflict occurs when vehicles do not yield to a pedestrian crossing in the parallel crosswalk.
- **Vehicles turning left on green.** This conflict occurs at intersections with permissive left turns where vehicles may be focused on selecting an acceptable gap in oncoming vehicular traffic and do not see and/or yield to a pedestrian in the conflicting crosswalk.
- **Vehicles running the red light.** This conflict is the most severe due to the high vehicular speeds often involved.

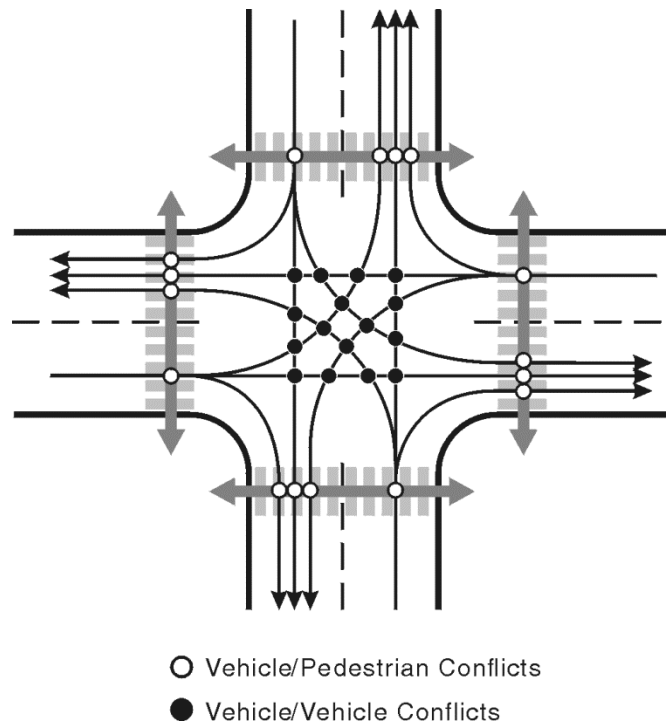


Exhibit 2-15. Pedestrian conflicts at signalized intersections.

Large signalized intersections with multiple lanes on each approach present the pedestrian with the possibility of having a vehicle in one lane yield but having a vehicle in the adjacent lane continue without yielding. The vehicle that has yielded may block the pedestrian's and other motorists' view of each other, thus putting the pedestrian at greater risk. This type of conflict may occur at signalized intersections in the following situations:

- *Double right-turn movements.* These take the form of either two exclusive right-turn lanes or one exclusive right-turn lane and a shared through-right lane.
- *Permissive double left-turn movements.* These are not common but are used in some jurisdictions, either with permissive-only phasing or with protected-permissive phasing.

Pedestrian Safety

Pedestrian safety must be a particular concern at signalized intersections, particularly those with a high volume of motorized vehicles. Pedestrians are vulnerable in an environment surrounded by large, powerful, and fast-moving vehicles. In 2009 there were 4,092 pedestrian fatalities involved in motor vehicle crashes, which represents 12 percent of all the 33,808 motor vehicle deaths.⁽²⁹⁾ An estimated 59,000 pedestrians were injured in motor vehicle collisions during this period.⁽²⁹⁾

Of all crashes between single vehicles and pedestrians in 2009, 1,063 (26 percent) occurred at intersections (both signalized and unsignalized).⁽¹⁸⁾ Speed plays a major role in motorist-pedestrian collisions, particularly fatalities; a pedestrian struck at 40 mph has an 85 percent chance of being killed, at 30 mph the probability of fatality is 45 percent, and at 20 mph the probability of fatality drops to 5 percent.⁽³⁹⁾ Compounding the problem, motorists rarely stop to yield to a pedestrian when their speeds are greater than 45 mph; they are likely to stop when their speeds are less than 20 mph.⁽⁴⁰⁾

From the driver's perspective, the mind goes through five psychological steps to "see" an object such as a pedestrian: selection, detection, recognition, location, and prediction. The speed

of the vehicle and the experience of the driver play critical roles in the driver's ability to detect pedestrians and react appropriately. Research shows that difficulties in information processing and driver perception contribute to approximately 40 percent of all traffic crashes involving human error.⁽⁴⁰⁾

The time required for a driver to detect a pedestrian, decelerate, and come to a complete stop is frequently underestimated or not even considered as part of the geometric design of an intersection. AASHTO's *A Policy on Geometric Design of Highways and Streets* states that a brake reaction time of 2.5 seconds is considered adequate for determining stopping sight distance.⁽³⁾ Additional research has suggested that the value of 2.5s has limitations and represents nearly ideal conditions with younger, alert drivers.⁽⁴¹⁾ The reaction time assumes an expected or routine condition such as a vehicle turning into or out of a driveway — more time is needed to account for an unexpected condition, such as a child darting into the street. A conservative perception-reaction time estimate for a “surprise” condition is 4.8 s.⁽⁴⁰⁾ Many things can impact the sight distance that allows the driver and pedestrian to see each other: landscaping, parked vehicles, traffic control devices, street furniture, etc. The practitioner must be mindful of these elements, particularly given that two-dimensional plans do not necessarily reflect the three-dimensional field of vision from the pedestrian and driver vantage points.

The combination of vehicle speed and visibility (or lack thereof) is a critical reason that the majority of motorists involved in pedestrian collisions claim that they “did not see them until it was too late.”⁽⁴⁰⁾

Accessibility for pedestrians is also a key element. The ADA of 1990 mandates, among other things, that transportation facilities be accessible to meet the diverse functional needs of people with disabilities.⁽⁷⁾ This requires that new or altered facilities be designed to allow pedestrians with access and functional needs to identify the crossing location, access the pushbutton, know when to cross, and know where to cross. The ADAAG published by the U.S. Access Board in 1991 identifies minimum design standards that must be applied to all new construction or alteration projects to adequately accommodate people with disabilities.⁽³⁶⁾ Accommodation of all users' needs should be included into the construction cost of an improvement. Note that facilities that are designed above the minimum standards generally improve the safety and accessibility for all pedestrians.

2.3 APPLYING HUMAN FACTORS

To reduce road user error at signalized intersections, the information necessary to permit relatively safe performance in an inherently hazardous environment must be effectively communicated. The design of the roadway network, including the intersections, should inherently convey what to expect to the various users. Road users must receive information in a form they can read, understand, and react to in a timely fashion. This information must reinforce common road user expectations or, if uncommon elements are present, emphatically communicate alternative information with sufficient time to react.

Failure to fully and adequately communicate the circumstances to be encountered by the road user increases the risk of hesitation, erroneous decision-making and incorrect action. Road users will rely on experience rather than their perceptions (however incomplete) of the situation at hand when their expectations are not met.

A fundamental premise of human factors is that insufficient, conflicting, or surprising information reduces both the speed and accuracy of human response. The following bullet items offer key information regarding the application of human factors principles in the analysis and design of a signalized intersection:

- All road users must first recognize signalized intersections before they can respond.
- All road users must have a clear presentation of the intersection on approach, or be appropriately forewarned by traffic control devices.
- Adequate visibility for nighttime operations is required.
- Navigational information must be available sufficiently in advance to allow for speed and path adjustments such as slowing to execute turns and lane changes.
- Signal indications must be visible from a sufficient approach distance for the user to perceive and react to changes in the assignment of right-of-way and the presence of queued traffic in a safe manner, according to the MUTCD.⁽¹⁾
- Phasing and change and clearance intervals for both vehicles and pedestrians must be suited to the characteristics and mix of road users using the intersection.
- The geometric aspects of the intersection, such as the presence of medians, curb radius, lane width, and channelization, and the implications of lane choices, must be clear.
- Points of potential conflict, particularly those involving vulnerable road users, must be evident and offer the approaching driver and pedestrian a clear view of each other.
- The route through the intersection itself must be explicit to avoid vehicles encroaching on each other.

CHAPTER 3

Data Collection and Warrants

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3.0 DATA COLLECTION AND WARRANTS

3.1 COMMITMENT

When an agency decides to install a signal, they make a long-term investment of resources at a specific point on the transportation network. Signals require consistent care throughout their life. For example, agencies must respond to emergency repairs such as power outages; adjust timing due to changing traffic patterns; replace outdated equipment as the state of technology changes; and monitor safety performance for all users.

3.2 WHERE DO YOU START? IMPORTANCE OF AN ENGINEERING ANALYSIS AND STUDY

When evaluating changes to intersection traffic control, engineers can refer to a wide range of research and best practices. Some examples are the ITE Traffic Engineer's Handbook, State DOT MUTCD manuals, and the Minnesota DOT Intersection Control Evaluation (ICE).⁽⁴³⁾ Engineers should keep in mind that signalizing an intersection has broad implications for the transportation network, both positive and potentially negative. For example:

- Signalizing an intersection can eliminate barriers to pedestrians created by arterials bisecting adjacent neighborhoods.
- Signals can attract drivers away from unintended by-pass routes that were previously used to avoid busy unsignalized intersections.
- Signals can reduce, but not eliminate, right angle crashes.
- Signals can significantly increase rear end crashes.

3.3 INTERSECTION DATA COLLECTION NEEDED

Studying an intersection requires a basic set of information. This list of information is not an exclusive list (e.g., in some cases detecting a horse in an Amish community is needed). However, the vast majority of intersections will require most of the items on this list:

- Number and turning movement of vehicles.
- Physical roadway attributes (e.g., number of lanes, approach grade).
- Vehicles' classification, especially specialty vehicles (e.g., school buses).
- Number of pedestrians.
- Number of bicyclists.
- Speed study of each approach.
- Knowledge of the region, such as surrounding development (e.g., large specific traffic generators).
- Location of transit stops and facilities.
- Most importantly, field observations of peak hours.

3.4 INTERSECTION COUNTS

Easily the most important piece of information that is needed to study an intersection is traffic count data. Reviewing the count is a starting point to understanding how traffic ebbs and flows throughout the day. An intersection count should cover 12 hours of a typical day and should be

conducted in 15-minute intervals. Counts typically occur manually or with automated count stations (see Exhibit 3-1). From the count, the engineer can easily start to see what movements are critical to the overall operation of the intersection.

3.4.1 What is a Typical Day?

Knowledge of the area may alter what is considered a “typical” day. A large recreational area or shopping area may require a weekend count. Recent advances in counting technology, such as automated intersection counting stations, make it easier to evaluate weekdays, weekends, holidays, and special events, and to perform counts longer than a standard, manual 12-hour count.



Exhibit 3-1. Automated intersection count station.

Source: Traffic Technology Today

<http://www.traffictechnologytoday.com/news.php?NewsID=39788>

3.4.2 Procedures for Future Intersections

Some agencies have enacted procedures to estimate traffic volumes for future intersections. Traffic impact studies commonly require estimated traffic volumes, typically completed using the guidelines found in the ITE Trip Generation Manual.⁽⁴²⁾ The practitioner should be able to generate the number of trips resulting from the proposed development. These trips are distributed over the street network to determine future traffic patterns. An engineer must be comfortable that actual traffic volume will be sufficient to require a traffic signal. Some planning agencies use traffic planning software to estimate future traffic patterns on the network. The MUTCD recommends evaluating the intersection after a year to be sure the initial assumptions were correct.

3.4.3 Vehicle Classification

Practitioners must also consider the expected types of vehicles when designing a signalized intersection. Intersection counts should capture this information. Examples of various vehicle combinations that should be counted or noted are:

- Tractor-trailer units in either single or combination trailers.
- City transit and tour buses.
- School buses.
- Large recreational vehicles in single or combination units.
- Emergency vehicles (e.g., ladder trucks).

Practitioners should note any vehicles larger than a WB-50 truck and their frequency of occurrence. These vehicles' large turning radius, long start up time, and safety impacts can affect intersection design. In some cases, larger vehicles can be calculated into Passenger Car Equivalents (PCEs) to account for their additional impacts on the system.

In addition, practitioners may adjust type and location of detection, timing parameter settings, and target lengths of turn lanes and auxiliary lanes to accommodate the queue needs of these larger vehicles.

3.4.4 Pedestrians

Pedestrians are the most vulnerable class of roadway users. Counting pedestrians is the first step to ensuring their needs are incorporated into the signal design and operations. This information is necessary to help practitioners develop signal timing and design pedestrian cross walks and refuge islands. Practitioners should also consider the environment in which an intersection is located. An area lacking in sidewalks may still have pedestrians to be accommodated at an intersection. This information can be collected during the intersection counts and should include the size of pedestrian groups, their frequency, and their walking speed.



Exhibit 3-2. Pedestrians crossing at a signal

Source: PBIC Image Library Alpena, Michigan, Dan Burden, 2006.

<http://www.pedbikeimages.org/pubdetail.cfm?picid=1019>

3.4.5 Bicyclists

Practitioners can also capture bicyclists' information during intersection counts. Bicyclists using crosswalks should be included in the pedestrian count.

3.4.6 Speed Study of Each Approach

ITE recommended practices for calculating clearance intervals requires assessing approach speeds. ITE recommends using the 85th and 15th percentile speeds for this purpose. Practitioners should also perform a "spot speed" survey for each approach. These surveys can be done manually using radar or automatically using counting technology. This information is also used to determine dilemma zone concerns.⁽⁴⁴⁾



Exhibit 3-3. Pennsylvania Ave., Washington, DC
Source: Google

3.4.7 Knowledge of the Region

Warrant analysis covers the basic reasons for installing a signal; however, a signal should also support the overall function of a regional transportation network. Signalized intersections offer the most benefits when installed at major street junctions. Signals should almost always enhance through movements of any major street while balancing access to minor streets and pedestrians. Practitioners should be aware that many mid-size cities and counties have identified key intersections in their long range transportation plan. These planning documents are often a small part of a larger planning effort that combines both transportation engineering and a vision for the community's future. Signals can also support completing connections between large industrial sites, mixed use developments, schools, and emergency services.



Exhibit 3-4. Pennsylvania Ave., Washington, DC
Source: Matthew Myers, 2011

3.5 TRAFFIC SIGNAL WARRANTS

Practitioners perform engineering studies of planned signalized intersections to predict their immediate and future impacts. The basis of every engineering study concerning signals is the set of warrants found in the MUTCD. The warrants are part of the basic principles in the MUTCD that govern the design and use of traffic control devices. In addition, Code of Federal Regulations (CFR) 655.603 adopts the MUTCD as the National standard for all traffic control devices installed on any street, highway, bikeway, or private road open to public travel (see definition in Section 1A.13). When a State or Federal agency manual or supplement is required, that manual or supplement shall be in substantial conformance with the National MUTCD.

3.5.1 What Do the Warrants Constitute?

The warrants represent the basic areas an engineer's analysis should cover: intersections where users have difficulty maneuvering through the intersection due to high mainline volumes; drivers trying to cross streets with inadequate gaps; and pedestrians trying to cross large expanses of pavement.

3.5.2 Volume Warrants

Warrant 1: Eight-Hour Vehicular Volume

Warrant 1, the Eight-Hour Vehicular Volume Warrant, is one of the most widely used and familiar warrants. It is a count of the number of entering vehicles at an intersection in an 8-hour period. The practitioner will review the operations of a "typical" day at the intersection. Overall, satisfying this warrant indicates that a signal can be a reasonable investment towards improving the overall efficiency and safety of the intersection.

The engineer will find two conditions under this warrant. The warrant is satisfied when one of the conditions is met. Condition A indicates that the total number of entering vehicles from every approach causes undue delay, and condition B is satisfied when an imbalance occurs between the major and minor route, causing undue delay to motorists entering from minor roads.

This warrant should cause the practitioner to ask "What is the typical day or week for this intersection?" For example, high-use recreational areas, such as a lake or shopping mall, are different than a city arterial serving large subdivisions.

Right-turning Vehicles. One question often asked by practitioners is, "How should we count right turning vehicle traffic?" Many times this movement is unimpeded and does not contribute to the approach delay or other operational deficiencies of the intersection. The engineer, through their judgment, may subtract the volume of right-turning vehicles from the warrant analysis, especially those turning from the side street. Practitioners should consult the policies of the local governing agency responsible for the intersection for possible details concerning right-turning vehicles.

Left-turning Vehicles – Major Approach. In some cases, major approach left turns may queue past the available storage and reduce the capacity of the approach. In this situation the engineer should consider using a heavy left turn off of the major approach to satisfy the minor approach volume. This is an example in which engineering judgment is necessary throughout a warrant analysis to determine if signalizing an intersection will improve the overall operations and safety of the intersection.

Warrant 2: Four-Hour Volume and Warrant 3: Peak Hour Volume

Both of these warrants address unusually high, short duration side street traffic volumes. Practitioners should take care when using these warrants. Many types of businesses generate these volumes at any given time. In most cases, this would not constitute justification for installing

a signal. In fact, some agencies place additional emphasis on making sure these warrants are used sparingly compared to Warrant 1.

3.5.3 Specialty Conditions

Warrant 4: Pedestrian Volume

This warrant is similar in application to the previous warrants. The data necessary are major street traffic volume and pedestrian volume, and the warrant is satisfied either for four hours or a single peak hour.

Many regions of the United States have recently placed a higher emphasis on non-motorized travel. However, many arterials were built to standards that created barriers to non-motorized users. Many cities now create networks focused on non-motorized travel. Signalizing intersections for pedestrians supports these networks. Agencies and practitioners implement treatments to improve the pedestrian safety, such as enhanced crosswalks using medians and signing. Agencies may also implement other available alternatives to traditional traffic signals, such as Pedestrian Hybrid Beacons (also known as High Intensity Activated Crosswalks (HAWKS)). Additional information on the Pedestrian Hybrid Beacon is available on the FHWA Office of Safety website at:

http://safety.fhwa.dot.gov/provencountermeasures/fhwa_sa_12_012.htm.

As more communities focus their efforts on non-motorized travel, facilities more widely support bicyclists and pedestrians. Bicyclists should be counted as either vehicles or pedestrians depending on how they enter the intersection. In a community with high bicycle use, practitioners will likely encounter both at an intersection.

Warrant 5: School Crossing

This warrant is similar to Warrant 4, but deals specifically with school age pedestrians. Installing a signal can eliminate the barrier created by a busy and wide intersection that pedestrians find difficult to cross safely. Practitioners are asked to measure the frequency of adequately sized gaps in traffic flow that permit the average group of school age children cross the major street. The warrant is met if no gaps occur.

The engineer should be aware of any policies or procedures the agency has in place for school crossings, such as requiring an adult crossing guard to supervise the crosswalk. Also, these signals may “rest” in green for the majority of the day, which can cause issues for drivers who do not expect them to change. Adding advance signing helps increase drivers’ awareness when the signal is active during selected hours of the day. Pedestrian hybrid signals, mentioned previously, are an alternative to traditional signals. The city of Tucson, Arizona has been successful with these types of treatments.

Warrant 6: Coordinated Signal System

Practitioners may need to use a signal to platoon traffic flow down a major road, improving the overall effectiveness of a signalized corridor. The MUTCD warns that this warrant should not be used if the intersection spacing is less than 1,000 ft. Warrant 6 is not widely used

For signal coordination purposes, the spacing between signals should range from $\frac{1}{4}$ to $\frac{1}{2}$ mile. Signal spacing less than 1,000 ft is difficult to coordinate.

Warrant 7: Crash Experience

Practitioners must analyze the intersection’s crash history as part of the engineering study. Many practitioners focus on the threshold listed in this warrant. Signals can provide some safety benefits under the right situations, but other crash types at the intersection can increase dramatically, especially rear end crashes. Often right angle crashes will decrease, but these crash types will not be completely eliminated.

Information related to assessing the impact of a traffic signal can be found in the following resources:

- Highway Safety Manual
- States Strategic Highway Safety Plans
- Crash Modification Factors (CMF) Clearinghouse website

These resources can help practitioners develop a focused, data-driven approach to reducing the severity of roadway crashes; screening the roadway network for intersections to review; quantifying safety impacts associated with modifying existing signalized intersections; and/or establishing the installation of a new signal.

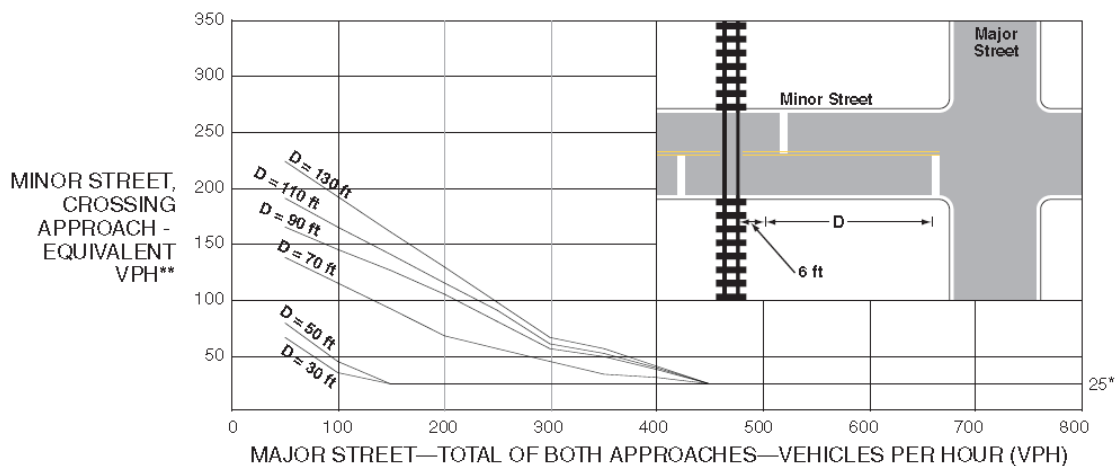
Warrant 8: Roadway Network

An efficient and safe network of transportation options requires significant effort by metropolitan planning organizations, regional planning commissions, cities, counties, and State DOTs. Increased travel demand due to regional growth necessitates change. Traffic control at arterial and other major roadway intersections requires maintaining adequate levels of user service. These organizations may have conducted preliminary studies to determine which intersections should be signalized intersections or roundabouts. Practitioners who are evaluating future traffic impacts due to signals should seek out this information from these organizations.

Warrant 9: Intersection near a Grade Crossing

Practitioners must ensure that drivers and other road users are able to clear railroad tracks to prevent any conflicts from approaching trains. The figures used in this warrant offer the practitioner guidance and information on factors related to buses, tractor-trailers, and frequency of trains per day. Figure 4C-9 from the MUTCD is one of the figures related to this warrant. This warrant addresses any intersection within 140 feet of a railroad track.

**Figure 4C-9. Warrant 9, Intersection Near a Grade Crossing
(One Approach Lane at the Track Crossing)**



* 25 vph applies as the lower threshold volume

** VPH after applying the adjustment factors in Tables 4C-2, 4C-3, and/or 4C-4, if appropriate

Exhibit 3-5. Warrant 9: Intersection near a Grade Crossing.

Source: MUTCD, 2009

Preemption control shall be provided at any signal near railroad tracks installed under this warrant, and any other signalized intersection that regularly queues traffic onto a set of tracks.

3.6 WHEN IS NOT SIGNALIZING AN INTERSECTION THE RIGHT DECISION?

This is one of the perplexing questions a practitioner and the general public may ask. The MUTCD acknowledges the importance of engineering judgment. The warrants represent best practice, but a signal can dramatically change traffic patterns. Signalized intersections should complement a transportation network, even if it is only an isolated signal. Corridors with closely or oddly spaced signals are difficult to time effectively and can cause a premature decline of the network.

CHAPTER 4

GEOMETRIC DESIGN

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4.0 GEOMETRIC DESIGN

This chapter presents geometric design guidelines for signalized intersections based on a review of technical literature and current design policy in the United States.

Geometric design of a signalized intersection involves the functional layout of travel lanes, curb ramps, crosswalks, bike lanes, and transit stops in both horizontal and vertical dimensions. Exhibit 4-1 illustrates the functional boundaries of a signalized intersection.

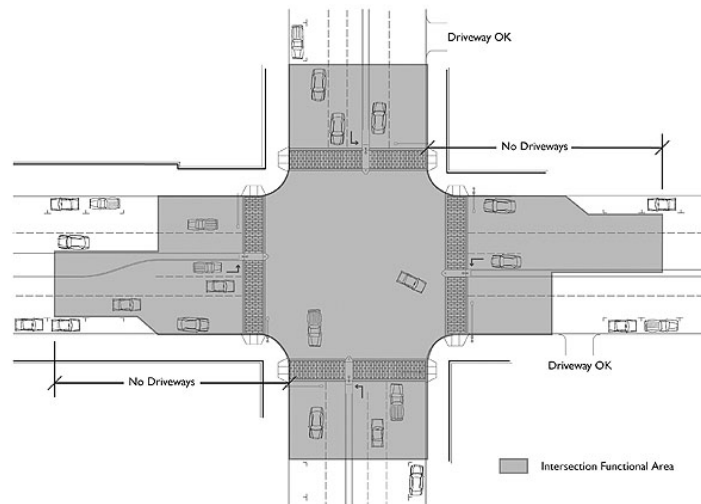


Exhibit 4-1. Intersection functional boundaries.

Source: "Intersection Design Guidelines," Institute of Transportation Engineers, <http://www.ite.org/css/online/DWUT10.html>

Geometric design profoundly influences roadway safety; it shapes road user expectations and defines how to proceed through an intersection where many conflicts exist. In addition to safety, geometric design influences the operational performance for all road users. Minimizing impediments, reducing the need for lane changes and merge maneuvers, and minimizing the required distance to traverse an intersection all improve intersection safety and operational efficiency.

All possible road users' (see Chapter 2) needs must be considered to achieve optimal safety and operational levels at an intersection. When road user groups' design objectives conflict, the practitioner must carefully examine the needs of each user, identify the tradeoffs associated with each element of geometric design, and make decisions with all road user groups in mind. For instance, practitioners may design corner radii to accommodate large vehicles. However, these larger radii would be detrimental to pedestrian safety due to the increase in walking distances and the increase in speed of turning vehicles. Exhibit 4-2 shows a typical example of this situation.



Exhibit 4-2. A large corner radius that impacts pedestrian safety.

Source: PBIC Image Library, Dan Burden

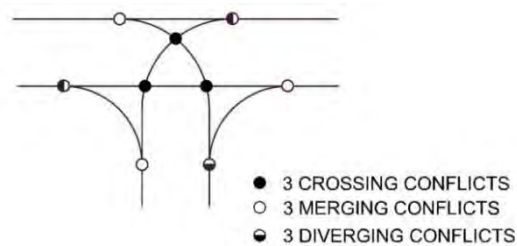
This chapter addresses the following topics:

- Number of intersection approaches.
- Principles of channelization.
- Horizontal and vertical alignment.
- Corner return radius access control.

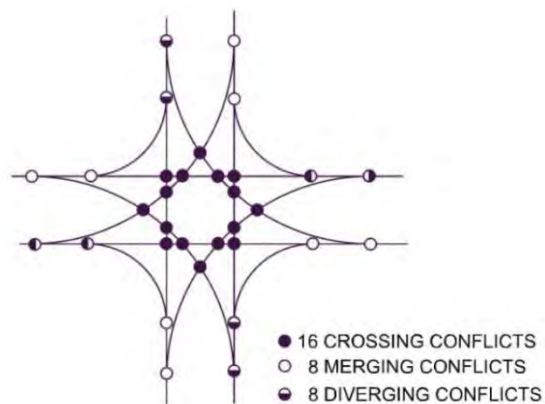
- Sight distances.
- Pedestrian treatments.
- Curb ramp design.
- Detectable warnings.
- Bicycle facilities.
- Transit facilities.

4.1 NUMBER OF INTERSECTION LEGS

The complexity of an intersection increases as the number of approach legs to the intersection increases. Exhibit 4-3, below, shows the number and type of conflicts that occur at intersections with three and four legs, respectively. Exhibit 4-4 shows a complex intersection with six approach legs. The number of potential conflicts for all users increases substantially at intersections with more than four legs. Note that many potential conflicts, including crossing and merging conflicts, can be managed (but not eliminated) at a signalized intersection by separating conflicts in time.



(a) Three-leg intersection.



(b) Four-leg intersection.

Exhibit 4-3. Potential conflicts at intersections with three and four legs.



Exhibit 4-4. Photograph of a six-leg intersection.
Source: Google 2012

4.2 CHANNELIZATION

A primary goal of intersection design is to limit and/or reduce the severity of potential road user conflicts. Basic principles of intersection channelization that can reduce conflicts are described below.⁽⁴⁵⁾

1. **Discourage undesirable movements.** Designers can utilize corner radii, raised medians, or traffic islands to prevent undesirable or wrong-way movements. Examples include:

- Restricting left turns from driveways or minor streets based on safety or operational concerns.
- Designing channelization to discourage wrong way movements onto freeway ramps, one-way streets, or divided roadways.
- Designing approach alignment to facilitate intuitive movements.

Exhibit 4-5 shows how a raised median can be used to restrict undesirable turn movements within the influence of signalized intersections.



Exhibit 4-5. This raised median restricts left-turn egress movements from a driveway located between two intersections.

Source: Google 2012

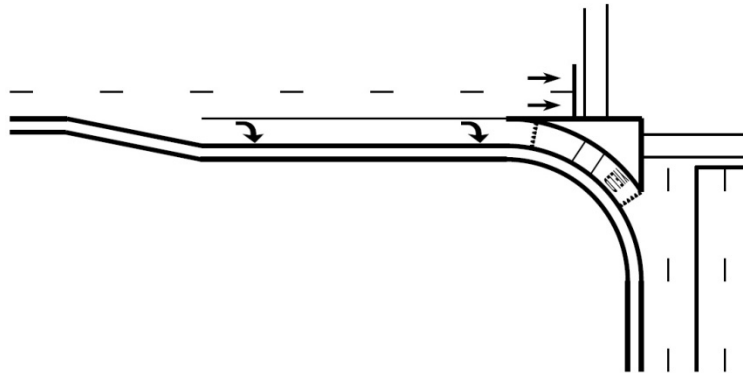
2. Define desirable paths for vehicles. The approach alignment to an intersection as well as the intersection itself should present the roadway user with a clear definition of the proper vehicle path. This is especially important at locations with complex geometry or traffic patterns such as highly skewed intersections, multi-leg intersections, offset-T intersections, and intersections with very high turn volumes. Clear definition of vehicle paths can minimize lane changing and avoid “trapping” vehicles in the incorrect lane. Avoiding these undesirable effects can improve both safety and traffic flow at an intersection. Exhibit 4-6 shows how pavement markings can be applied to delineate travel paths.



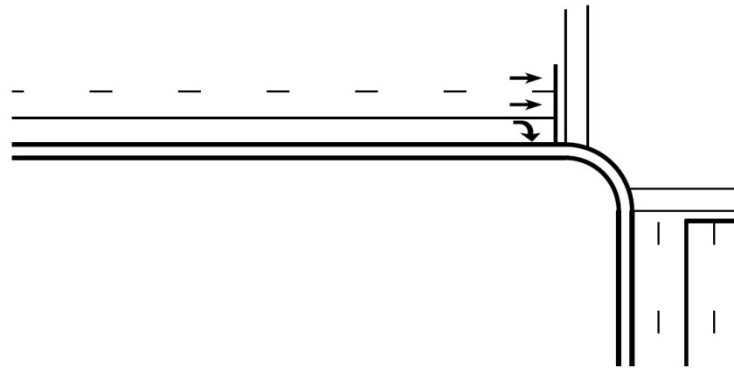
Exhibit 4-6. Single point urban intersection (SPUI) with pavement marking delineation for turning movements.

Source: Google 2012

3. **Encourage safe speeds through design.** Effective intersection design promotes desirable speeds to optimize intersection safety. The appropriate speed will vary based on the use, type, and location of the intersection. On high-speed roadways with no pedestrians, practitioners may want to promote higher speeds for turning vehicles to remove turning vehicles from the through traffic stream as quickly and safely as possible. This can be accomplished with longer, smooth tapers and larger corner radii. On low-speed roadways or in areas with pedestrians, practitioners may want to promote lower turning speeds. This can be accomplished with smaller turning radii, narrower lanes, and/or channelization features. These are illustrated in Exhibit 4-7.



(a) Higher speed design

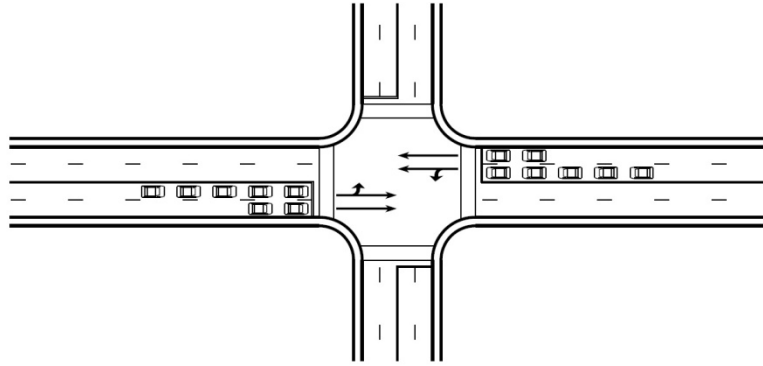


(b) Lower speed design

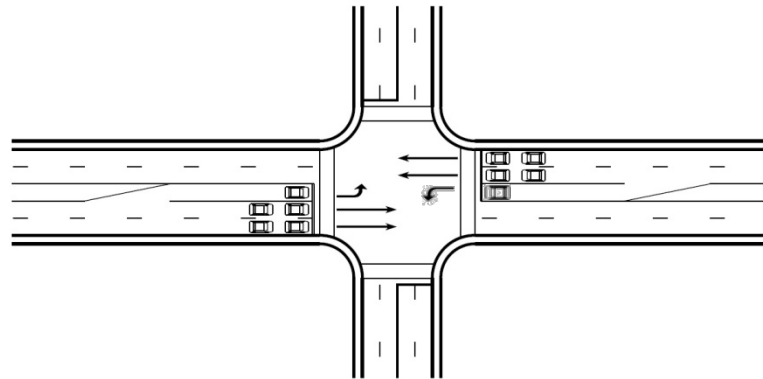
Exhibit 4-7. Various right-turn treatments may be used, depending on the speed environment.

Chapter 11 contains information pertaining to individual movements such as right- and left-turn lanes, including details concerning storage, multiple turn lanes, and warrants.

4. **Separate points of conflict where possible.** Separation of conflict points can ease the driving task while improving both the capacity and safety at an intersection. The use of exclusive turn lanes, channelized right turns, and raised medians as part of an access control strategy are all effective ways to separate vehicle conflicts. Exhibit 4-8 illustrates how the addition of a left-turn lane can reduce conflicts with through vehicles traveling in the same direction.



(a) Major street with shared left-through lane causes through vehicles to queue behind left-turning vehicles.



(b) Major street with dedicated left-turn lane removes left-turning vehicles from the paths of through vehicles.

Exhibit 4-8. Providing a dedicated left-turn lane reduces potential rear end collisions between left-turning and through vehicles, increasing the capacity of the approach for both left and through traffic.

5. Facilitate the movement of high-priority traffic flows. Accommodating high-priority movements at intersections addresses both drivers' expectations and intersection capacity. The highest movement volumes at an intersection, define the highest priority movements, although practitioners may also consider route designations and functional classification of intersecting roadways. In low density suburban and rural areas, it may be appropriate to give priority to motor vehicle movements; however, in some urban locations, pedestrians and bicyclists at times may be the highest priority users of the road system. Exhibit 4-9 shows an intersection where double and triple left-turn lanes are used to facilitate high-volume turning movements. Information concerning when these treatments are warranted can be found in Chapter 11.



Exhibit 4-9. The photo shows how double and triple left-turn lanes can be used to accommodate high-priority movements.
Source: Google 2012

6. **Facilitate the desired traffic control scheme.** The signalized intersection design should allow the agency to accommodate changing traffic patterns throughout the life of the intersection. Practitioners should ensure that intersection signs and markings are clearly understood and support correct driver decisions. Other equipment at the intersection should not block sight distance and should facilitate preventive maintenance by field personnel. Practitioners should design for simultaneous left-turning movements and potential u-turning movements. Operational impacts and the design of pedestrian facilities should be taken into account during the intersection's design.

7. **Accommodate decelerating, slow, or stopped vehicles outside higher speed through traffic lanes.** Speed differentials between vehicles in the traffic stream are a primary cause of traffic crashes. Speed differentials at intersections are inherent as vehicles decelerate to facilitate turning. The provision of exclusive left- and right-turn lanes can improve safety by removing slower moving turning vehicles from the higher speed through-traffic stream and reducing potential rear-end conflicts. In addition, through movements may experience lower delay and fewer queues.



Exhibit 4-10. Pedestrian refuge and bicyclist way finding.

Source: Steven Vance, 2010.

8. Provide safe refuge and way finding for bicyclists and pedestrians. Intersection design must consider non-motorist roadway users' needs. Intersection channelization can provide refuge and/or reduce the exposure distance for pedestrians and bicyclists within an intersection without limiting vehicle movement. Practitioners should also consider using raised medians, traffic islands, and other pedestrian-friendly treatments during the design process. Way finding may also be an issue, particularly at intersections with complicated configurations. Practitioners can address this through pavement marking and signing, as shown in Exhibit 4-10.

In locations where the horizontal or vertical alignment obscures raised or flush channelization or markings, practitioners may need to extend the limits of channelization or use other methods to call the attention of road users. For example, should the limits of raised channelization begin at the crest of a vertical curve, it should be extended to give motorists ample time to perceive and react to its presence. In an instance where a right-turn lane taper begins within the outside of a horizontal curve, the channelization or marking may be slightly exaggerated to indicate the presence of the tapered area.

4.3 HORIZONTAL AND VERTICAL ALIGNMENT

The approach to a signalized intersection should promote awareness of the intersection by providing the required stopping sight distance in advance of the intersection. This area is critical as the approaching driver or bicyclist begins to focus on the tasks associated with navigating the intersection.

Drivers' or bicyclists' expectations on approaches to an intersection could be violated under the following conditions, and mitigation efforts should be considered:

- Approach grades to an intersection of greater than 3 percent.
- Intersections located along a horizontal curve of the intersecting road.
- Intersection tables (including sidewalks) with a cross slope exceeding 2 percent.

The angle of the intersection of two roadways can influence both the safety and operational characteristics of an intersection. Heavily angled intersections not only affect the nature of conflicts, but they produce larger, open pavement areas that can be difficult for drivers to navigate and pedestrians to cross. Such large intersections can also be more costly to build and maintain.

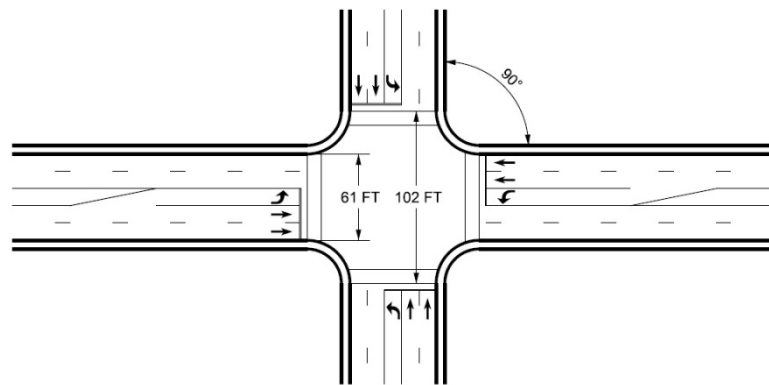
Undesirable operational and safety characteristics of skewed intersections include:

- Difficulty accommodating large vehicle turns. Additional pavement, channelization, and right-of-way may be required. The increased pavement area poses potential drainage problems and gives smaller vehicles more opportunity to "wander" from the proper path. Enhanced pavement marking or color-treated pavement can sometimes address this issue.
- Vehicles crossing the intersection are more exposed to conflicts. This requires longer change and clearance intervals and increased lost time, which reduces the capacity of the intersection.
- Longer pedestrian and bicyclist exposure to vehicular traffic. Longer pedestrian intervals may be required, which may have a negative impact on the intersection's capacity.
- Pedestrians with visual disabilities may have difficulty finding their way to the other side of the street when crossing.
- Driver confusion may be more likely at skewed crossings. Woodson, Tillman, and Tillman found that drivers are more positive in their sense of direction when roadways are at right angles to each other.⁽⁴⁶⁾ Conversely, drivers become more confused as they traverse curved or angled streets.

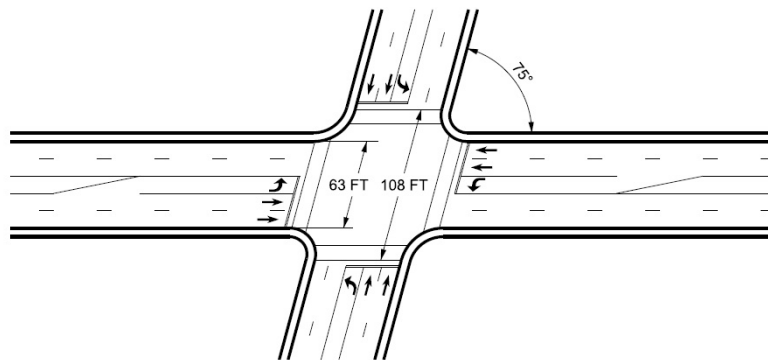
Angled intersections tend to have more frequent right-angle type crashes associated with poor sight distance. AASHTO policy and many State design standards permit angled intersections between 60 to 90 degrees.⁽³⁾ NCHRP Report 500, Volume 12 (Signalized Intersections) recommends 75 degrees or greater to avoid the issues related older drivers, turning right on red, and judging gaps for left-turn maneuvers.

Gattis and Low conducted research to identify constraints on the angle of a left-skewed intersection as it is affected by a vehicle body limiting a driver's line-of-sight to the right.⁽⁴⁷⁾ Their findings suggest that if roadway engineers are to consider the limitations created by vehicle design, a minimum intersection angle of 70 to 75 degrees will offer an improved line-of-sight. FHWA's *Highway Design Handbook for Older Drivers and Pedestrians* recommends intersection angles of 90 degrees for new intersections where right-of-way is not a constraint, and angles of not less than 75 degrees for new facilities or redesigns of existing facilities where right-of-way is restricted.⁽¹⁵⁾

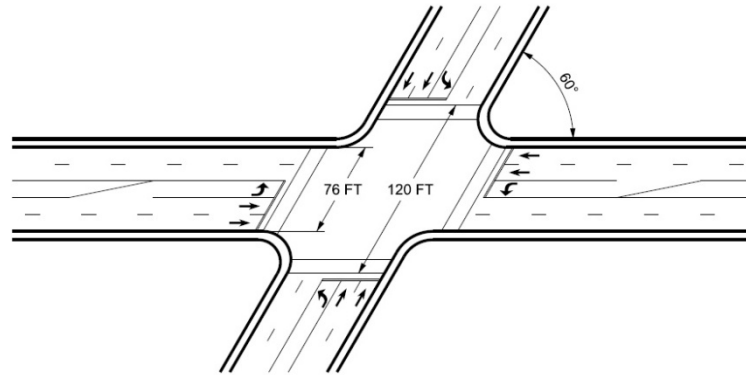
Practitioners should strive to design approaches to intersect at or near right angles. Exhibit 4-11 shows how an angled intersection approach can increase the distance to clear the intersection for pedestrians and vehicles.



(a) Intersection angle at 90 degrees (i.e., no skew)



(b) Intersection angle at 75 degrees (i.e., 15-degree skew)



(c) Intersection angle at 60 degrees (i.e., 30-degree skew).

Exhibit 4-11. Intersection angle increases both the intersection width and pedestrian crossing distance.

It should be noted that the intersection angle and intersection skew, by definition, are complimentary angles. The HSM shows that intersection skew is measured from orthogonal, as shown in Exhibit 4-12.

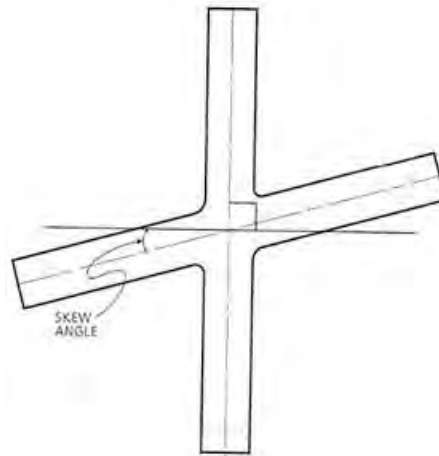


Exhibit 4-12. Intersection skew.

4.4 CORNER RADIUS

Appropriately designed intersection corners accommodate all users. Practitioners should select corner radii and curb ramp design based upon pedestrian crossing and design vehicle needs at the intersection. In general, pedestrian crossings should be as near to perpendicular to the flow of traffic as practical with no intermediate angle points. This keeps pedestrian crossing time and exposure to a minimum, which may allow for more efficient operation of the signal. It also aids visually impaired pedestrians in their way finding task by eliminating changes in direction that may not be detectable.

Practitioners should design corner radii to accommodate the turning path of a design vehicle to avoid encroaching on pedestrian facilities and opposing lanes of travel. Section 4.6.1 addresses curb ramp design in greater detail.

Larger intersection curb radii have disadvantages for pedestrians. Larger radii increase pedestrian crossing distance and the speeds of turning vehicles, creating increased exposure risks. This can be particularly challenging for pedestrians with impaired vision. Large radii also reduce the corner storage space for pedestrians, move pedestrians out of the driver's line of sight, and make it more difficult for pedestrians to see vehicles. On the other hand, smaller radii limit the speeds of turning vehicles and may reduce the operational efficiency of an arterial intersection. A curb that protrudes into the turning radius of the design vehicle can cause vehicles to drive over and damage the curb, as well as increase the potential of hitting a pedestrian standing at the curb.⁽⁴⁸⁾

Factors that influence the selection of appropriate corner radii include the following:

- **Design vehicle.** Selection of a design vehicle should be based on the largest vehicle type that will regularly use an intersection. This can be represented as a standard passenger car, motor home, single-unit truck, bus or semi-trailer. The AASHTO *Green Book* describes representative design vehicles parameters. Practitioners should select an appropriate design vehicle based on the existing and anticipated type of use and the tradeoffs involved with design and spatial impact, and with input from stakeholders and the public. They should select the largest class of vehicle that uses the facility on a regular as the design vehicle. It should represent a cost-effective choice for the project and be appropriate for its context. Use of the facility by the design vehicle should be both a measurable (i.e., over 0.5 percent) and reasonably predictable percentage of the average daily traffic.⁽⁴⁹⁾ Often, agency policy will mandate a design vehicle, regardless of vehicle mix. In certain instances, more than one design vehicle may be appropriate, depending on traffic patterns. There may be instances where it is necessary to consider flush radii instead of raised curbs. By incorporating flush radii, vehicles with large turning radii can be accommodated without modifications to curbed sections. However, not all situations are ideal for flush radii; practitioners should consider the volume and type of non-motorized transportation and locations of intersection infrastructure.
- **Angle of intersection.** Large intersection skew angles necessitate non-matching corner radii, as well as very large or very small radii to accommodate the skew.
- **Pedestrians and bicyclists.** In areas of high pedestrian and bike use, smaller radii are desirable to reduce turning speeds and decrease the distance for pedestrians and bikes to cross the street.
- **Constraints.** Multi-centered curves or simple curves with tangent offsets may better match the turn path of the design vehicle and reduce required right-of-way. Additional pavement may be added to either curbed or flush radii to serve as a truck apron.
- **Encroachment.** A designer must consider whether a turning vehicle's wheel path or swept path should encroach into adjacent lanes (same direction), flush islands that separate traffic, or even into opposing lanes. This concept is important in both right- and left-turn maneuvers. The curb return radii imposed on raised median islands may affect the ability to maintain speed and safely make left turns for motorists leaving or arriving at the approach. Traffic signal infrastructure located within the radius of a right turn maneuver may be damaged due to encroaching vehicles.
- **Intersection size.** Corner radius influences the overall width of the intersection. While larger radii allow for use by vehicles with larger turning radii, it may increase the crossing distance for pedestrians and lengthen overall intersection delay.

4.5 SIGHT DISTANCE

Drivers' ability to see the road ahead and other intersection users is critical to safe and efficient use of all roadway facilities, especially signalized intersections. Stopping sight distance, decision sight distance, and intersection sight distance are particularly important at signalized

intersections. It is imperative that drivers be given sufficient distance to perceive, recognize, and react to the presence of traffic control elements such as traffic signal indications, pavement markings, and signing, in addition to the possibility of queued vehicles and the need to maneuver into auxiliary lanes prior to the intersection.

4.5.1 Stopping Sight Distance

Stopping sight distance is the roadway distance required for a driver to perceive and react to an object in the roadway and to brake to a complete stop before reaching that object. Designers should provide sufficient stopping sight distance to road users throughout the intersection and on each entering and exiting approach. Exhibit 4-13 gives recommended stopping sight distances for design, as computed from the equations provided in the AASHTO policy.⁽³⁾

Exhibit 4-13. Design values for stopping sight distance.

Speed (km/h)	Computed Distance* (m)	Design Distance (m)	Speed (mph)	Computed Distance* (ft)	Design Distance (ft)
20	18.5	20	15	76.7	80
30	31.2	35	20	111.9	115
40	46.2	50	25	151.9	155
50	63.5	65	30	196.7	200
60	83.0	85	35	246.2	250
70	104.9	105	40	300.6	305
80	129.0	130	45	359.8	360
90	155.5	160	50	423.8	425
100	184.2	185	55	492.4	495
110	215.3	220	60	566.0	570
120	248.6	250	65	644.4	645

* Assumes 2.5 s perception-braking time, 11.2 ft/s² (3.4 m/s²) driver deceleration

Source: American Association of State Highway and Transportation Officials (AASHTO). *A Policy on Geometric Design of Highways and Streets*. Washington, DC: AASHTO, 2011.

Practitioners should calculate stopping sight distance using an assumed height of driver's eye of 3.5 ft and an assumed height of object of 2.0 ft.⁽³⁾

4.5.2 Decision Sight Distance

Decision sight distance is “the distance needed for a driver to detect an unexpected or otherwise difficult-to-perceive information source or condition in a roadway environment that may be visually cluttered, recognize the condition or its potential threat, select an appropriate speed and path, and initiate and complete the maneuver safely and efficiently.”^(3, p. 115) Decision sight distance at intersections applies to situations where vehicles must maneuver into a particular lane in advance of the intersection (e.g., alternative intersection designs using indirect left turns).

Decision sight distance varies depending on whether the driver is to come to a complete stop or make some kind of speed, path, or direction change. Decision sight distance also varies depending on the environment—urban, suburban, or rural. Exhibit 4-14 gives recommended values for decision sight distance, as computed from equations in the AASHTO policy.⁽³⁾

Exhibit 4-14. Design values for decision sight distance for selected avoidance maneuvers.

Speed (mph)	U.S. Customary (ft)				
	A	B	C	D	E
30	220	490	450	535	620
35	275	590	525	625	720
40	330	690	600	715	825
45	395	800	675	800	930
50	465	910	750	890	1030
55	535	1030	865	980	1135
60	610	1150	990	1125	1280
65	695	1275	1050	1220	1365

Avoidance Maneuver A: Stop on rural road, time (t) = 3.0 s.

Avoidance Maneuver B: Stop on urban road, t = 9.1 s.

Avoidance Maneuver C: Speed/path/direction change on rural road, t = 10.2 s to 11.2 s.

Avoidance Maneuver D: Speed/path/direction change on suburban road, t = 12.1 s to 12.9 s.

Avoidance Maneuver E: Speed/path/direction change on urban road, t = 14.0 s to 14.5 s.

Source: American Association of State Highway and Transportation Officials (AASHTO). *A Policy on Geometric Design of Highways and Streets*. Washington, DC: AASHTO, 2011.

4.5.3 Intersection Sight Distance and Line of Sight

The distance drivers without right-of-way at signalized intersections require to perceive and react to the presence of traffic signal indications, conflicting vehicles, and pedestrians is the intersection sight distance. Horizontal and vertical sight distance must also be maintained such that roadway users have an adequate line-of-sight to traffic control elements as they approach the intersection. Any overhead structure could cause a sight obstruction to nearby traffic signal heads. Practitioners should take care to design the structure and/or modify traffic control devices such that overhead structures do not obstruct approaching road users' view of traffic signals (and other elements like signing). Exhibit 4-15 shows an example where an overhead walkway obstructs the line-of-sight approaching a signalized intersection.



Exhibit 4-15. A pedestrian grade separation treatment restricts sight distance of the traffic signal as motorists approach the intersection.

Source: Synectics Transportation Consultants, Inc.

Practitioners should refer to the AASHTO *Green Book* for a complete discussion of intersection sight distance requirements.⁽³⁾ Intersection sight distance at signalized intersections is generally simpler than at stop-controlled intersections. The following criteria should be met:

- The first vehicle stopped on an approach should be visible to the first driver stopped on each of the other approaches.
- Vehicles making permissive movements (e.g., permissive left turns, right turns on red, etc.) should have sufficient sight distance to select gaps in oncoming traffic.
- Permissive left turns should satisfy the case for left turns from the major road.
- Right turns on red should satisfy the case for a stop-controlled right turn from the minor road.

However, the sight distance needed for stop-controlled intersections should always be maintained for signalized intersections in the event that traffic signals are installed to flash for emergency situations or during instances of power failure where the traffic signal indications are dark.

Intersection sight distance is traditionally measured through the determination of a sight triangle. This triangle is bound by a length of roadway defining a limit away from the intersection on each of the two conflicting approaches and by a line connecting those two limits. Intersection sight distance should be measured using an assumed height of driver's eye of 3.5 ft and an assumed object height of 3.5 ft.⁽³⁾ The area within the triangle is referred to as the sight triangle, and any object at a height above the elevation of the adjacent roadways that would obstruct the driver's view should be removed or lowered, if practical. Such objects may include buildings, parked vehicles, highway structures, roadside hardware, hedges, trees, bushes, un-mowed grass, tall crops, walls, fences, and terrain itself. Exhibit 4-16 illustrates intersection sight distance triangles that should be designed and maintained for all signalized intersections.

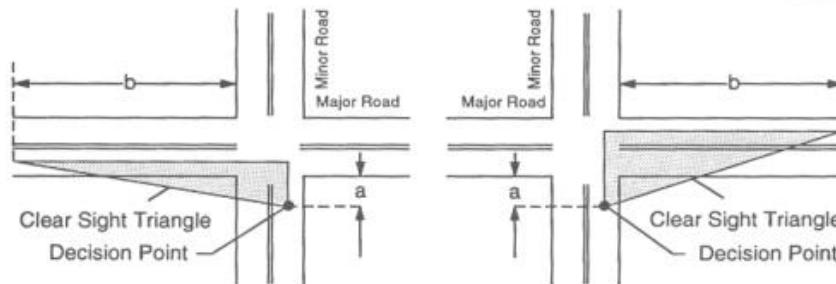


Exhibit 4-16. Intersection sight distance.

Source: Modified from the American Association of State Highway and Transportation Officials (AASHTO) publication *Policy on Geometric Design of Highway and Streets*, 5th Edition, 2004.

4.6 PEDESTRIAN TREATMENTS

It is the policy of the USDOT to “incorporate safe and convenient walking and bicycling facilities into transportation projects,” which is accomplished by working with State and local agencies that receive Federal-aid funding to plan, design and implement these features.⁽¹⁹⁷⁾ Furthermore, in 2008, the FHWA Office of Safety included walkways on its list of Proven Safety Countermeasures, recognizing their significant safety benefits.⁽¹⁹⁸⁾ Therefore, practitioners should provide for pedestrian facilities at all intersections in urban and suburban areas, and at any intersection with known or expected pedestrian activity. This is especially important for signalized intersections, since additional equipment is needed to accommodate pedestrians.

In general, practitioners should design the pedestrian facilities of an intersection with the most challenged users in mind, those pedestrians with mobility or visual impairments. The resulting design will serve all pedestrians well. The *Proposed Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way* provides technical requirements and advisory information pertaining to the design, construction, and alteration of facilities such that they are made accessible to and usable by individuals with disabilities. The guidelines take into consideration three laws that require newly constructed and altered facilities to be accessible to individuals with disabilities: the Americans with Disabilities Act, Section 504 of the Rehabilitation Act, and the Architectural Barriers Act.⁽⁵⁴⁾ Therefore, providing pedestrian facilities that are accessible is not merely a matter of best practice, it is also the law.

Pedestrians may face a number of disincentives to walking, including centers and services located far apart, physical barriers and interruptions along pedestrian routes, perceptions that routes are unsafe due to motor vehicle conflicts or crime, and esthetically unpleasing routes.⁽⁵⁰⁾

Certain key elements of pedestrian facilities that practitioners should incorporate into their design are listed and described below.^(Adapted from 51)

- **Pedestrian route.** Ensure the routes and crossings are free of barriers, obstacles, and hazards. Ensure curb ramps, transit stops (where applicable), equipment such as pushbuttons, etc., are well located and meet accessibility standards.
- **Exposure to traffic.** Clearly indicate where crossings should occur and the actions pedestrians are expected to take at crossing locations. Limit exposure to conflicting traffic by minimizing the crossing distance as much as practical, ensure the crosswalk is a direct continuation of the pedestrian's travel path and provide refuges where advantageous.
- **Roadside features.** Provide a separation buffer between the nearest vehicular travel lane and the pedestrian route. Keep corners free of obstructions to provide enough room for pedestrians waiting to cross. Design corner radii to ensure that vehicles do not encroach into pedestrian areas.
- **Visibility and conspicuity.** Strive to design facilities so that pedestrians and traffic are mutually visible by maintaining adequate lines of sight between drivers and pedestrians, especially at crosswalks. When intersection lighting is provided, arrange the lighting to achieve positive contrast of pedestrians.
- **Level of service.** Provide appropriate and regular intervals for crossings and minimize wait time for pedestrians.

4.6.1 Curb Ramp Design

Curb ramps provide access for people who use wheelchairs and scooters. Curb ramps also help people with strollers, luggage, bicycles, and other wheeled objects negotiate the intersection. The basic components of a curb ramp, including ramp, landing, detectable warning, flare, and approach, are diagrammed in Exhibit 4-17. The *Proposed Accessibility Guidelines for Pedestrian Facilities in the Public Right-of-Way* reflects the technical requirements for curb ramps as stated in the ADA and ABA Accessibility Guidelines (ADAAG). The ADAAG requires that curb ramps be provided wherever an pedestrian route crosses a curb, which includes crosswalks at new and retrofitted signalized intersections.⁽³⁶⁾ While curb ramps increase access for mobility-impaired pedestrians, they can decrease access for visually impaired pedestrians by removing the vertical curb face that provides an important tactile cue. This tactile cue is instead provided by a detectable warning surface (DWS) placed at the bottom of the ramp, which provides information on the boundary between the sidewalk and roadway. More information about DWS can be found later in this chapter.

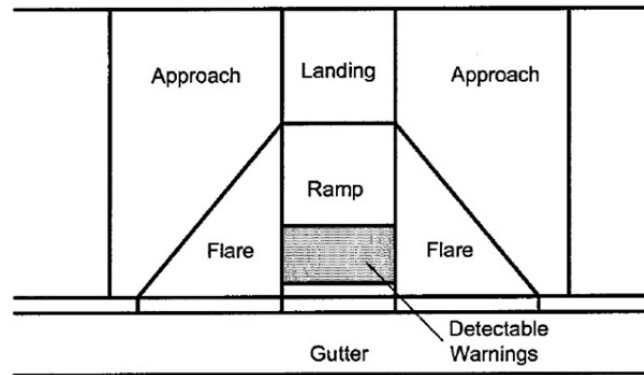
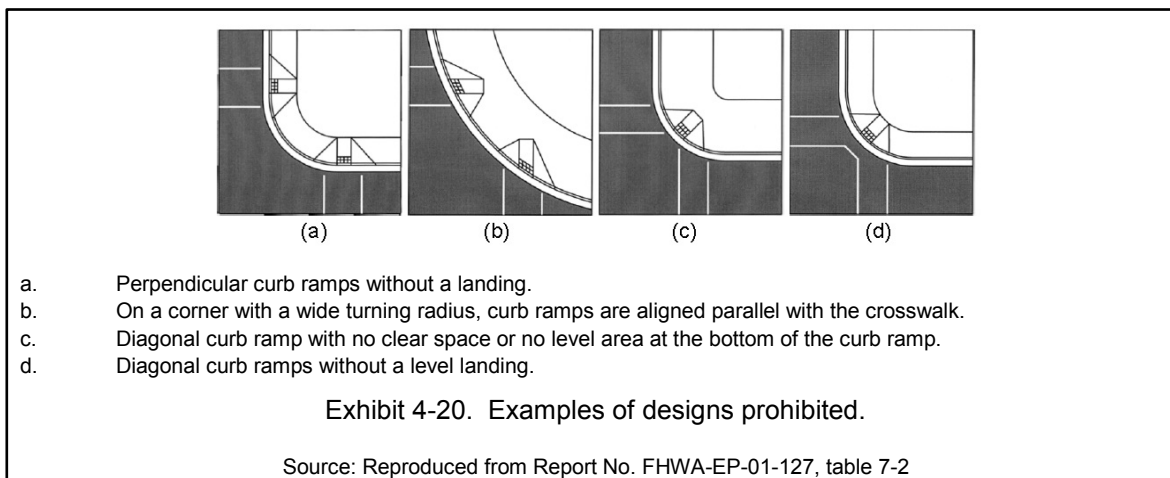
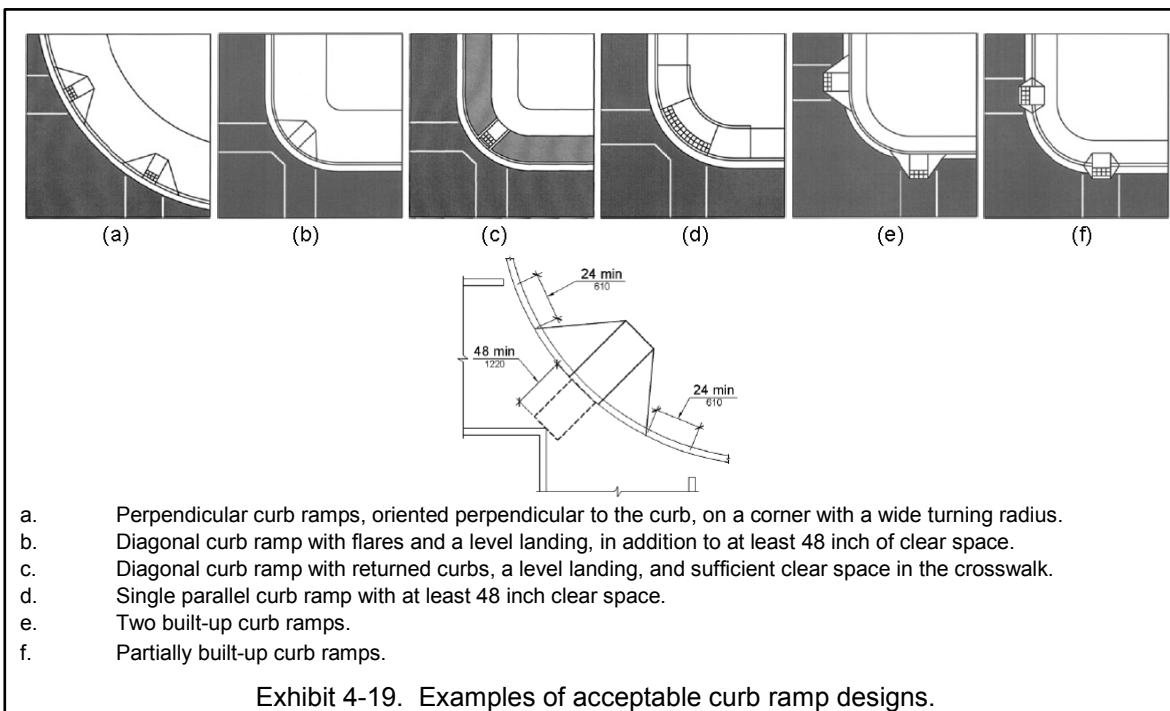
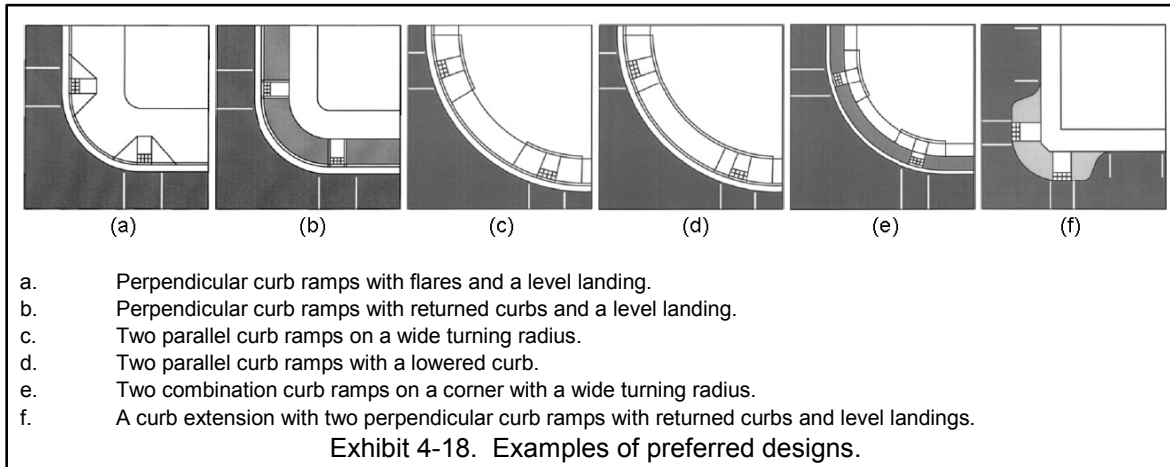


Exhibit 4-17. Curb ramp components

The AADAG provides designers with *Survey Form 4: Curb Ramps* to help in development of accessible curb ramps that meet the requirements of the AADAG, available at <http://www.access-board.gov/adaag/checklist/CurbRamps.html>. Designers may also use FHWA's *Designing Sidewalks and Trails for Access, Part 2: Best Practices Design Guide*, as a source of recommended fundamental practices for curb ramp design, along with the rationale behind each practice.⁽³⁷⁾ A designer can apply these principles in designing intersections in a wide variety of circumstances.

Exhibits 4-18, 4-19, and 4-20 provide examples of three categories of typical curb ramp treatments used at signalized intersections: those that should be implemented wherever possible ("preferred designs"), those that meet minimum accessibility requirements but are not as effective as the preferred treatments ("acceptable designs"), and those that are inaccessible and therefore should not be used in new or retrofit designs ("inaccessible designs"). Additional guidance and design details can be found in the source document.⁽³⁷⁾



4.6.2 Detectable Warning Surfaces

ADAAG and PROWAG require that a detectable warning surface (DWS) be provided at the bottom of curb ramps and within the refuge of any medians and islands (defined in the ADAAG as “hazardous vehicle areas”) to provide tactile cues to individuals with visual impairments so they can determine where the pedestrian route crosses traffic.⁽³³⁾ Detectable warning surfaces consist of a pattern of truncated domes built in or applied to walking surfaces. The domes provide a distinctive surface detectable by cane or underfoot. This surface alerts visually impaired pedestrians of the presence of the vehicular travel way. They also provide physical cues to assist pedestrians in detecting the boundary from sidewalk to street where curb ramps and blended transitions are devoid of other tactile cues typically provided by a curb face.

At the face of a curb ramp and within the refuge area of any median island, a detectable warning surface should be applied, as shown in Exhibit 4-21. The U.S. Access Board and FHWA encourage the use of the design pattern and application found in the 2011 PROWAG.



Exhibit 4-21. This crosswalk design incorporates the use of detectable warning surfaces into the curb ramps to facilitate navigation by a visually impaired pedestrian.

Source: Lee Rodegerdts, 2003

4.7 BICYCLE FACILITIES

Some intersections have on-street bicycle lanes or off-street bicycle paths entering the intersection. When this occurs, intersection design should accommodate the needs of bicyclists in safely navigating such a large and often complicated intersection. Some geometric features that should be considered include:

- Bike lanes and bike lane transitions between through lanes and right-turn lanes. Widths are typically 4 ft when curb and gutter are not present and 5 feet when the lane is adjacent to parking, from the face of the curb or guardrail.⁽²⁶⁾
- Left turn bike lanes.
- Median refuges with a width to accommodate a bicycle: 6 ft = poor; 8 ft = satisfactory; 10 ft = good.^(26, p. 52)

The interaction between motor vehicles and bicyclists at interchanges with merge and diverge areas is especially complex. Some signalized intersections also have merge and diverge areas due to free right turns or diverted movements. AASHTO recommends that “[i]f a bike lane or route must traverse an interchange area, these intersection or conflict points should be designed to limit the conflict areas or to eliminate unnecessary, uncontrolled ramp connections to urban roadways.”⁽²⁶⁾

Figure 9C-4. Example of Bicycle Lane Treatment at a Right Turn Only Lane

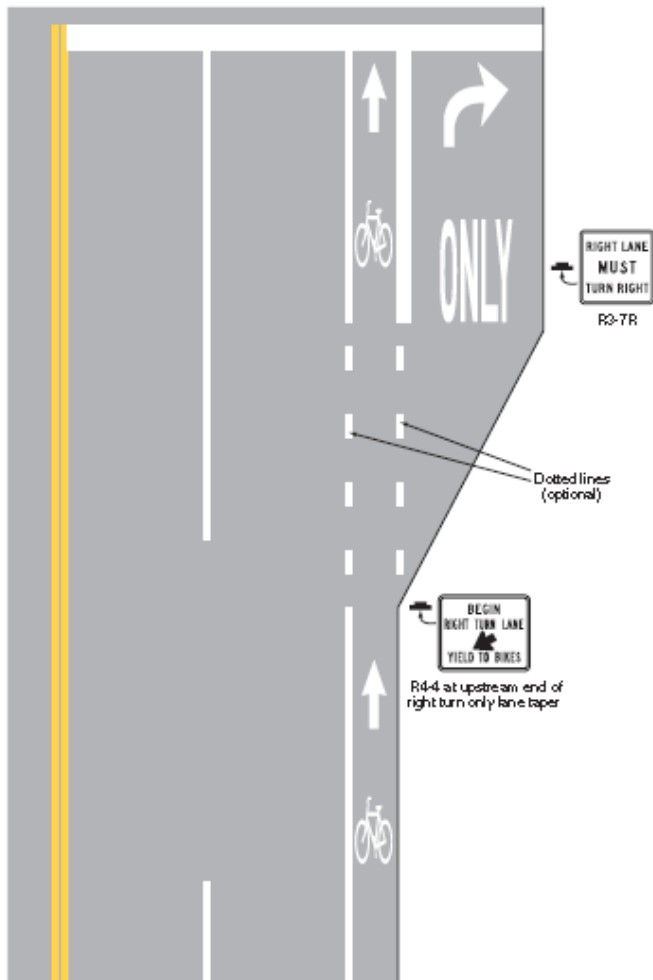


Exhibit 4-22. MUTCD diagram of right-turn lane bicycle accommodation
Source: 2009 MUTCD, Figure 9C-4.

4.8 TRANSIT FACILITIES

Transit facilities near intersections are commonplace in urbanized areas and occur in some rural areas. The placement of the bus stop can impact the safety and operational performance of the intersection. A discussion of transit facilities is included in Section 9.3 of Chapter 9, Intersection-Wide Treatments.



Exhibit 4-23. Transit facility in Santa Barbara, CA
Source: PBIC Image Library, Dan Burden, 2006

CHAPTER 5

TRAFFIC SIGNAL DESIGN AND ILLUMINATION

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5.0 TRAFFIC SIGNAL DESIGN AND ILLUMINATION

This chapter addresses traffic signal hardware and software—the infrastructure that controls the assignment of right-of-way for all intersection users, including vehicles, pedestrians, emergency vehicles, transit operators, trucks, and light-rail transit vehicles at locations where conflicts or hazardous conditions exist. The proper application and design of the traffic signal is a key component in improving the safety and efficiency of the intersection.

This chapter presents an overview of the fundamental principles of traffic signal design and illumination as they apply to signalized intersections. The topics discussed include:

- Traffic signal control types.
- Traffic signal phasing.
- Vehicle and pedestrian detection.
- Traffic signal pole layout.
- Traffic signal controllers.
- Basic signal timing parameters.
- Signing and pavement marking.
- Illumination.

5.1 TRAFFIC SIGNAL PHASING

The MUTCD defines a signal phase as the right-of-way, yellow change, and red clearance intervals in a cycle that are assigned to an independent traffic movement or combination of traffic movements.⁽¹⁾ Signal phasing is the sequence of individual signal phases or combinations of signal phases within a cycle that define the order in which various pedestrian and vehicular movements are assigned the right-of-way. The MUTCD provides rules for determining controller phasing, selecting allowable signal indication combinations for displays on an approach to a traffic control signal, and determining the order in which signal indications can be displayed.

Signal phasing at many intersections in the United States makes use of a standard National Electrical Manufacturers Association (NEMA) ring-and-barrier structure, shown in Exhibit 5-1. This structure organizes phases to prohibit conflicting movements (e.g., eastbound and southbound through movements) from timing concurrently, while allowing non-conflicting movements (e.g., northbound and southbound through movements) to time together. Most signal phasing patterns in use in the United States can be achieved through the selective assignment of phases to the standard NEMA ring-and-barrier structure.

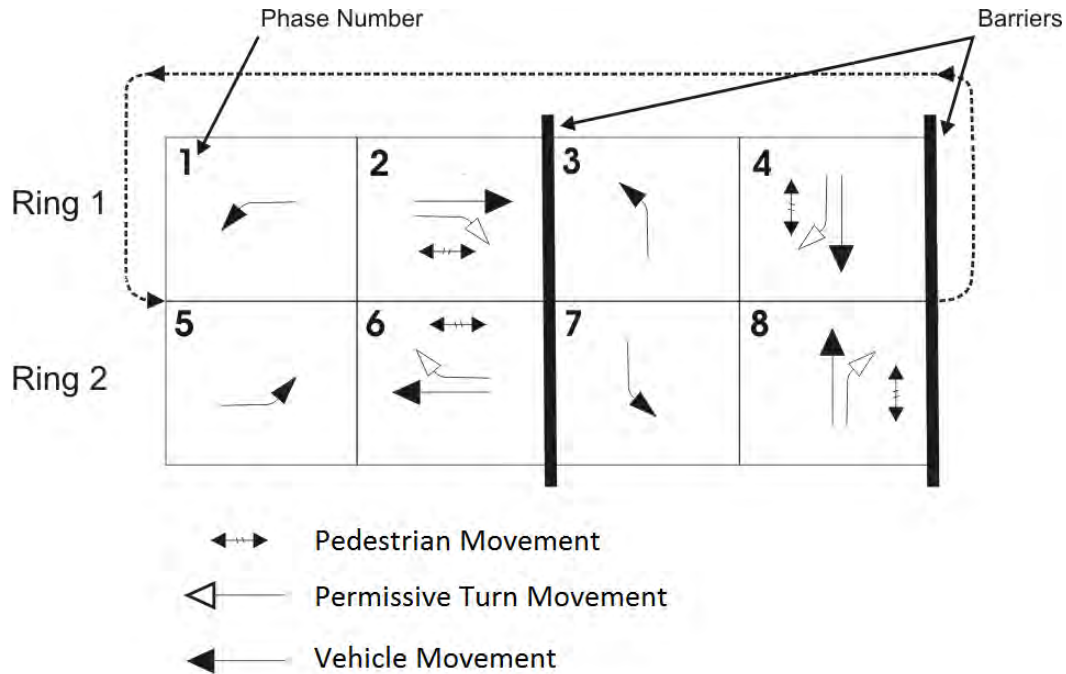


Exhibit 5-1. Standard NEMA ring-and-barrier structure.

Depending on the complexity of the intersection, two to eight phases are typically used, although most controllers provide far more phases to serve complex intersections or sets of intersections. Pedestrian movements are typically assigned to parallel vehicle movements.

Developing an appropriate phasing plan begins with determining the left-turn phase type at the intersection. The most basic form of control for a four-legged intersection is “permissive only” control, which allows drivers to make left turns after yielding to conflicting traffic and pedestrians and provides no special protected interval for left turns. As a general rule, practitioners should keep the number of phases to a minimum because each additional phase in the signal cycle reduces the time available to other phases, and each phase has its own startup delay time.

Provision of a separate left-turn lane, while not required, is recommended when providing a separate left-turn phase. Left-turn lanes increase operational efficiency by providing storage space where vehicles can await an adequate gap without blocking other traffic movements at the intersection. Left-turn lanes also increase the safety of an intersection by reducing rear-end and left-turn crashes. In most cases, the development of a signal phasing plan should involve an engineering analysis of the intersection. Several software packages are suitable for selecting an optimal phasing plan for a given set of geometric and traffic conditions for both individual intersections and for system optimization.

Practitioners must consider all intersection users during the development of a phasing plan, including pedestrians, bicyclists, transit vehicles, older drivers, and children. For example, on wide roadways pedestrian timing may require timing longer than what is required for vehicular traffic, which may have an effect on the operation analysis. The presence of older pedestrians or children may require a longer pedestrian clearance interval based on their slower walking speeds.

5.1.1 “Permissive-Only” Left-Turn Phasing

“Permissive-only” (also called “permitted-only”) phasing allows two opposing approaches to time concurrently, with left turns allowed after motorists yield to conflicting traffic and pedestrians. Exhibit 5-2 illustrates one possible implementation of this phasing pattern. Note that the two

opposing movements could be run in concurrent phases using two rings; for example, the eastbound and westbound through movements shown in Exhibit 5-2 could be assigned as phase 2 and phase 6, respectively.

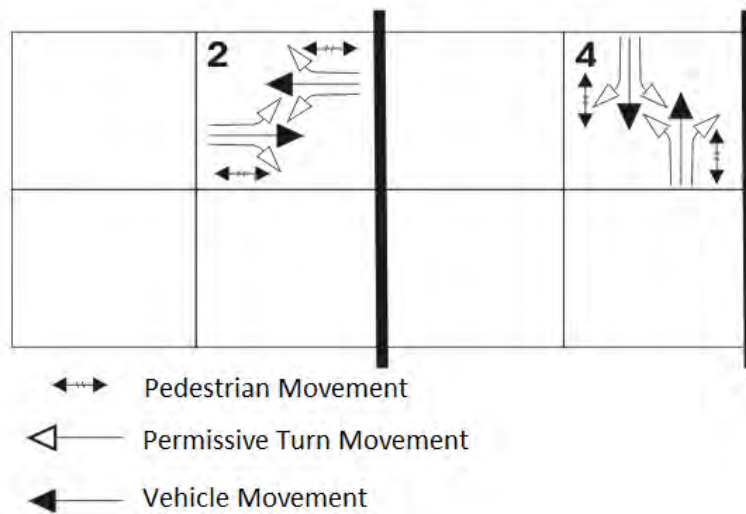


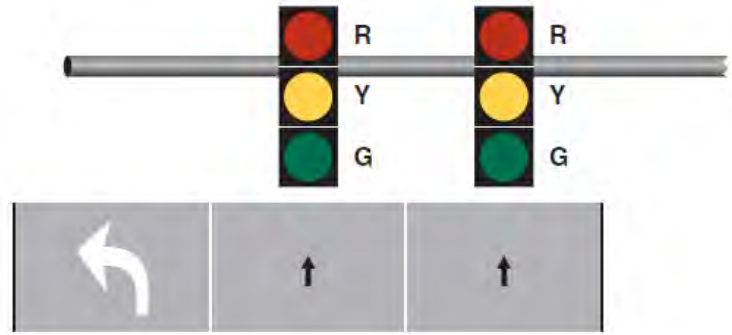
Exhibit 5-2. Typical phasing diagram for “permissive-only” left-turn phasing.

For most high-volume intersections, “permissive-only” left-turn phasing is generally not practical for major street movements because safety will be compromised in such situations, including left-turn safety. Minor side street movements, however, may function acceptably using “permissive-only” left-turn phasing, provided that traffic volumes are low enough to operate efficiently and safely without additional left-turn protection.

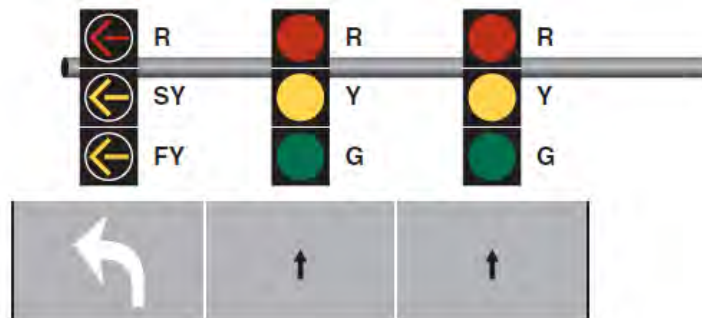
“Permissive-only” displays are signified most commonly in one of two ways. In the first case, if there is not an exclusive signal head assigned to a left-turn movement; instead, a three-section head with a circular green, circular yellow, and circular red is used. In this case, no regulatory sign is required.

In the second case, if there is a traffic signal head aligned with an exclusive left-turn lane, a three-section head with a flashing yellow arrow, steady yellow arrow, and steady red arrow is used.

As traffic volumes increase at the intersection, the number of adequate gaps to accommodate left-turning vehicles on the permissive indication may result in safety concerns at the intersection. Exhibit 5-3 shows common signal head arrangements that implement “permissive-only” phasing; refer to the MUTCD for other configurations.



(a) Permissive left-turn phasing using three-section signal heads over the through lanes only.



(b) Permissive left-turn phasing using three-section signal heads over the through lanes and a three-section signal head over the left turn lane.

Exhibit 5-3. Possible signal head arrangements for “permissive-only” left-turn phasing
(Source: 2009 MUTCD)

5.1.1 “Protected-Only” Left-Turn Phasing

“Protected-only” phasing consists of providing a separate phase for left-turning traffic and allowing left turns to be made only on a green left arrow signal indication, with no pedestrian movement or vehicular traffic conflicting with the left turn. As a result, left-turn movements with “protected-only” phasing have a higher capacity than those with “permissive-only” phasing due to fewer conflicts. However, under lower volume conditions, this phasing scheme can cause an increase in delay for left-turning drivers. Exhibit 5-4 illustrates this phasing pattern. Typical signal head and associated signing arrangements that implement “protected-only” phasing are shown in Exhibit 5-5; refer to the MUTCD for other configurations. Chapter 11 of this document provides guidance on determining the need for protected left turns.

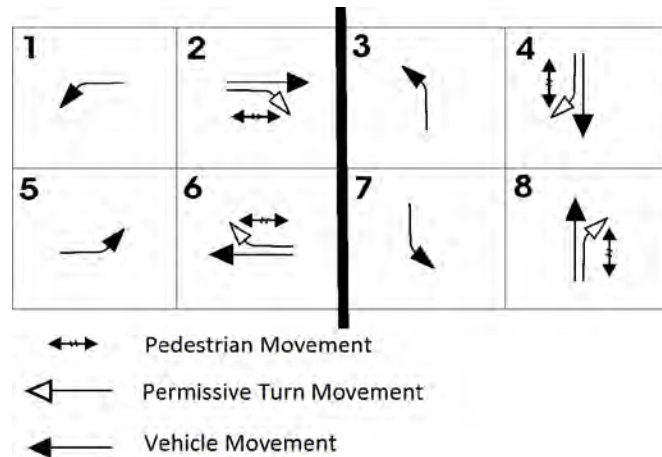
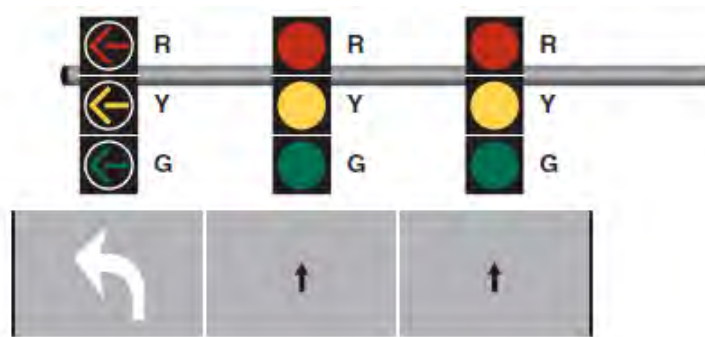


Exhibit 5-4. Typical phasing diagram for “protected-only” left-turn phasing.

Exhibit 5-5. Possible signal head arrangement for “protected-only” left-turn phasing
(Source: 2009 MUTCD)

5.1.2 Protected-Permissive Left-Turn Phasing

A combination of protected and permissive left-turn phasing is referred to as protected-permissive left-turn (PPLT) operation. Exhibit 5-6 illustrates this phasing pattern. The 2009 MUTCD allows two different signal phasing techniques for this type of operation. The first is when the left-turn lane and the adjacent through lane share the same signal head. Exhibit 5-7(a) shows a typical signal head and associated signing arrangement that implements this type of protected-permissive phasing (refer to the MUTCD for other configurations).

The second phasing technique involves a separate signal head provided exclusively for a left-turn movement. In this case, the flashing yellow arrow is used for the permissive portion of the left-turn movement. Exhibit 5-7(b) shows a typical signal head and associated signing arrangement that implements this type of protected-permissive phasing (refer to the MUTCD for other configurations).

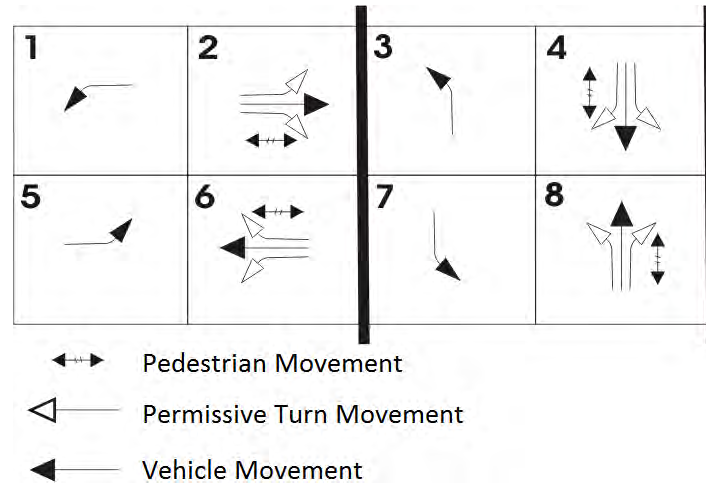
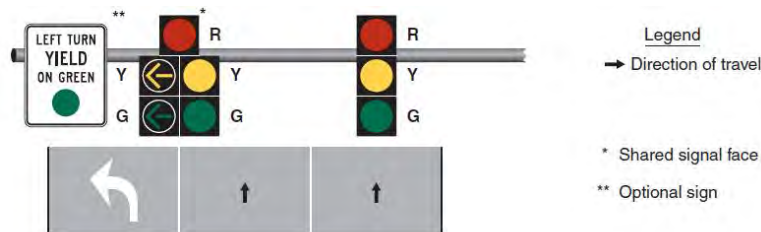
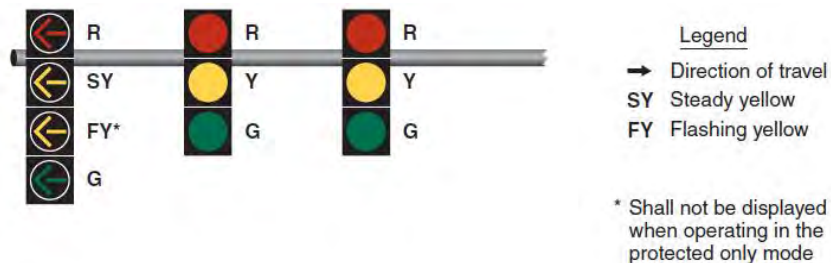


Exhibit 5-6. Typical phasing diagram for protected-permissive left-turn phasing.



(a) Protected-permissive left-turn phasing using a five-section head located directly above the lane line that separates the exclusive through and exclusive left-turn lane, along with an accompanying optional sign.



(b) Protected-permissive left-turn phasing using a five-section signal head located directly above the exclusive left-turn lane.

Exhibit 5-7. Possible signal head and signing arrangement for protected-permissive left-turn phasing.

Source: 2009 MUTCD

Observed improvements in signal progression and efficiency combined with driver acceptance have led to expanded usage of PPLT over the years. PPLT signals offer operational advantages when compared to “protected-only” operation. In protected-permissive phasing, consideration can be given to when in the cycle the protected left-turn movement is given. Where

both protected left-turn movements on opposing approaches operate before the permissive phase, it is known as lead-lead operation. Conversely, where the permissive phases operate before the protected left-turn movements on opposing approaches, it is known as lag-lag operation. Lead-lag operation involves a protected left-turn movement on one approach, while the opposite left-turn movement experiences a permissive left-turn. They include the following (adapted with additions by the authors):⁽⁵⁶⁾

- Average delay per left-turn vehicle is reduced.
- Protected green arrow time is reduced.
- There is potential to omit a protected left-turn phase.
- Arterial progression can be improved, particularly when special signal head treatments are used to allow lead-lag phasing.

The primary disadvantage of the permissive phase is an increased potential for vehicle-vehicle and vehicle-pedestrian conflicts. Younger and older drivers especially have difficulties interpreting the sufficient gap distance need to safely make permissive left turns. The use of permissive phasing also leaves pedestrians without a protected walk phase.

The controller phasing for protected-permissive mode is the most complicated phasing because of the safety implications created by the potential of a “yellow trap” occurring.

For ordinary lead-lead operations where both protected left-turn phases precede the permissive phases, the yellow trap does not occur, as both permissive phases end concurrently. However, this problem can occur when a permissive left turn is opposed by a lagging protected left turn. In this type of operation (known as lag-permissive), the yellow display seen by a left-turning driver is not indicative of the display seen by the opposing through driver. The opposing through display might remain green when the yellow signal indication is displayed to the permissive left-turn movement. A driver who turns left believing that the opposing driver has a yellow or red display when the opposing driver has a green display may be making an unsafe movement. Exhibit 5-8 illustrates this yellow trap.

Drivers who encounter this trap have entered the intersection on a permissive green waiting to make a left turn when sufficient gaps occur in opposing through traffic. If the absence of gaps in opposing through traffic requires them to make their turn during the yellow change or red clearance interval, they may be “stranded” in the intersection because of the absence of gaps and because the opposing through movement remains green. More importantly, they may incorrectly presume that the opposing through traffic is being terminated at the same time that the adjacent through movement is being terminated. Therefore, they may complete their turn believing that the opposing vehicles are slowing to a stop when in fact the opposing vehicles are proceeding into the intersection with a circular green signal indication.

There are options to eliminate the yellow trap situation. The first, and arguably best, option is the flashing yellow arrow operation for the permissive left-turn movement that became allowable with the 2009 MUTCD.

However, there may be circumstances in which that option is not feasible. If that is the case, the phase sequence at the intersection can be restricted to simultaneous leading (lead-lead) or lagging (lag-lag) left-turn phasing. However, it should be noted that under very light side street volumes, the leading left-turn phase can be activated such that it operates like a lagging left turn. This can be prevented using detector switching or a diode in the controller cabinet.

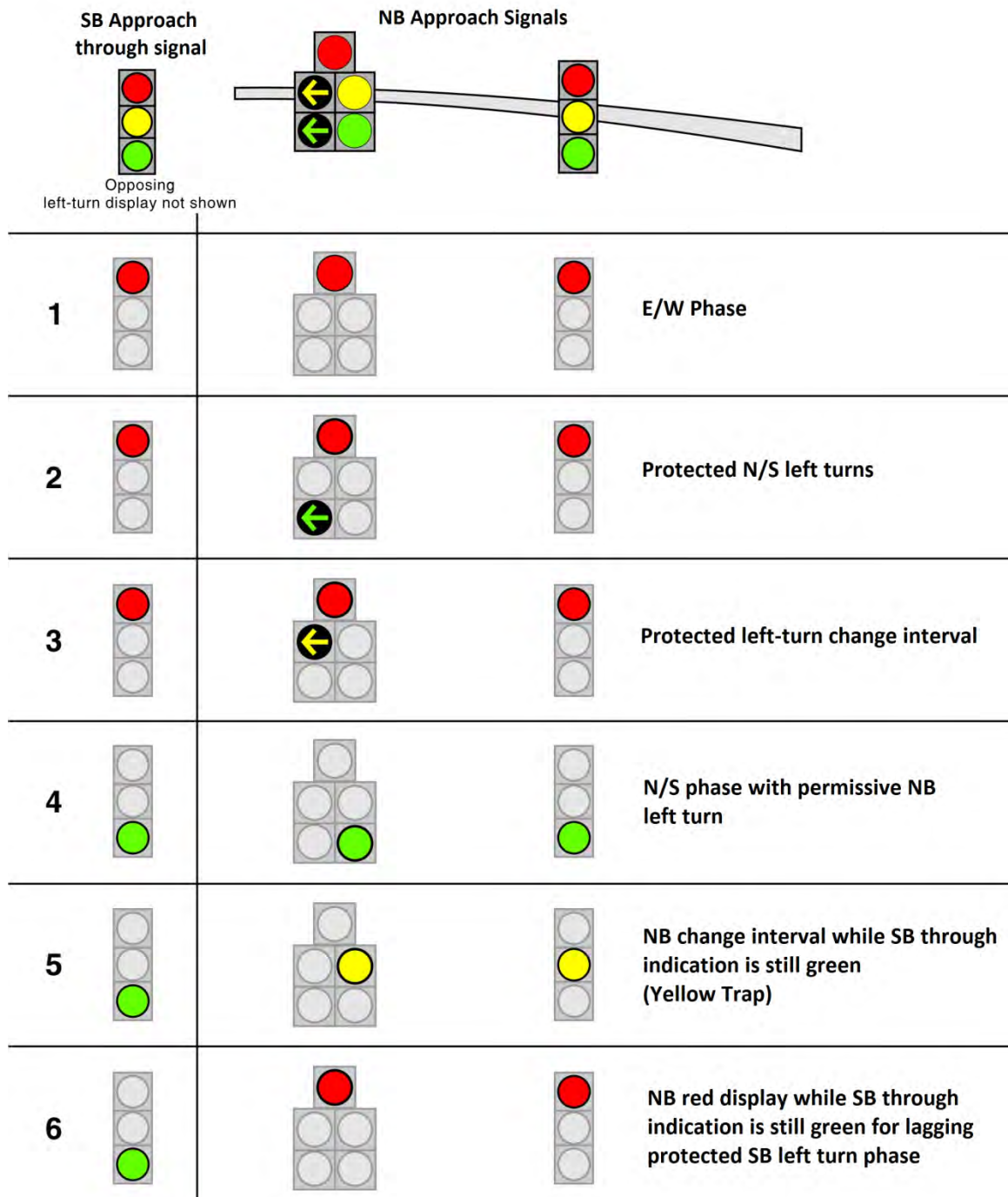


Exhibit 5-8. Illustration of the yellow trap.

5.1.3 Split Phasing

Split phasing consists of having two opposing approaches timed consecutively rather than concurrently (i.e., all movements originating from the west followed by all movements from the east). Split phasing can be implemented in a variety of ways, depending on signal controller capabilities and how pedestrian movements are treated.

Because of the inefficiency of a split phasing operation, it should only be considered after other operational methods or geometric solutions have been considered. In general, a new intersection should not be designed such that split phasing will be required. However, the following conditions could indicate that split phasing might be an appropriate design choice:

- **Multiple Turn Lanes.** There is a need to accommodate multiple turn lanes on an approach, but sufficient width is not available to provide separate lanes. Therefore, a shared through/left lane is required. Practitioners should perform an operational analysis to ensure this option is superior to a single turn lane option under various phasing scenarios.
- **Varied Traffic Volumes.** The left-turn lane volumes on two opposing approaches are approximately equal to the through traffic lane volumes, and the total approach volumes are significantly different on the two approaches. Under these somewhat unusual conditions, split phasing may prove more efficient than conventional phasing.
- **Offset Approach Issues.** A pair of opposing approaches is physically offset such that the opposing left turns could not proceed simultaneously or a permissive left turn could not be expected to yield to the opposing through movement.
- **Geometry.** The geometry of the intersection is such that the paths of opposing left turns would not be forgiving of errant behavior by turning motorists.
- **Crash History.** The safety experience indicates an unusual number of crashes (usually sideswipes or head-on collisions) involving opposing left turns. This may be a result of unusual geometric conditions that impede visibility of opposing traffic.
- **Lane Usage.** A pair of opposing approaches each has only a single lane available to accommodate all movements, and the left turns are heavy enough to require a protected phase.
- **Discrepant Demand.** One of the two opposing approaches has heavy demand and the other has minimal demand. Under this condition, the signal phase for the minimal approach would be skipped frequently and the heavy approach would function essentially as the stem of a T-intersection.

The MUTCD does not provide a standard method for indicating split phasing at an intersection. The methods vary considerably depending on what type of phasing sequence has been used. Exhibit 5-9 shows one way to implement split phasing that does not require the use of additional signs. It involves using a four-section head displaying both a circular green and a green left-turn arrow simultaneously.

However, additional measures are needed when the left-turn arrow would conflict with a concurrent pedestrian phase.⁽⁵⁷⁾

- A special logic package can suppress the green arrow display when serving the pedestrian phase.
- A static sign indicating “LEFT TURN YIELD TO PEDS ON GREEN (symbolic circular green)” located next to the leftmost signal head for emphasis.
- A blankout sign indicating “LEFT TURN YIELD TO PEDS” activated when the conflicting vehicular and pedestrian phases run concurrently.

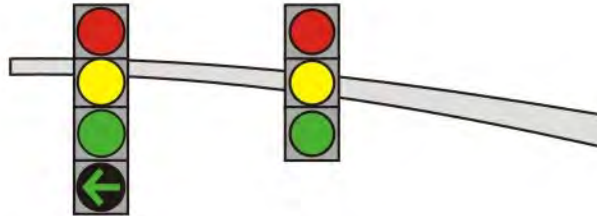


Exhibit 5-9. Common signal head arrangement for split phasing.

5.1.4 Prohibited Left-Turn Movements

Prohibiting left-turn movements at the intersection is an alternative to providing a left-turn phase. Under this scenario, left-turning drivers must divert to another facility or turn in advance of or beyond the intersection via a geometric treatment such as a jug handle or a downstream median U-turn. Left turns can be prohibited on a full- or part-time basis. The amount of traffic diverted, effects on transit routes, the adequacy of the routes likely to be used, and community impacts are all important issues to consider when investigating a turn prohibition. FHWA's Alternative Intersections and Interchanges Informational Report discusses a variety of treatments for redirecting left turns.⁽⁵⁸⁾

5.1.5 Right-Turn Phasing

Practitioners may control right-turn phasing in a permissive or protected manner with different configurations depending on the presence of pedestrians and the lane configurations at the intersections.

Right turns can operate on overlap phases to increase efficiency for the traffic signal. An overlap is a set of outputs associated with two or more phase combinations. As described earlier, practitioners can assign various movements to a particular phase. In some instances, right-turn movements operating in exclusive lanes can be assigned to more than one phase that is not conflicting. In this instance, a right turn is operated at the same time as the left turn, as shown in Exhibit 5-10. The overlap forms a separate movement deriving its operation from its assigned phases (also called parent phases); for example, overlap A (OL A) is typically assigned to phase 2 (the adjacent through phase) and phase 3 (the non-conflicting left-turn phase from the cross street).

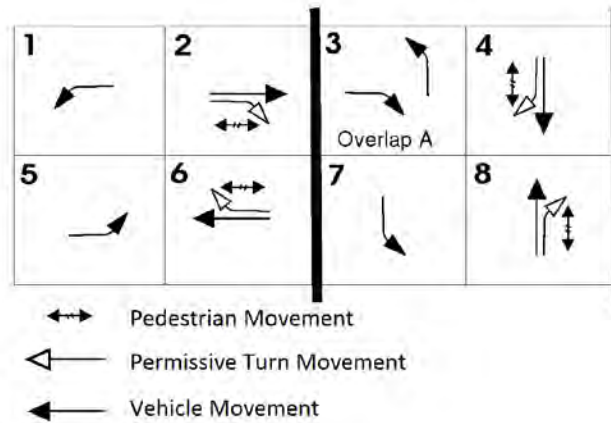


Exhibit 5-10. Typical phasing diagram illustrating a right-turn overlap.

A five-section head with a combination of circular and arrow indications is more commonly used. Note that the MUTCD requires the display of a yellow change interval between the display of a green right-turn arrow and a following circular green display that applies to the continuing right-turn movement on a permissive basis. This yellow change interval is necessary to convey the change in right-of-way from fully protected during the green arrow to requiring a yield to pedestrians and other vehicles during the circular green. This can be implemented by assigning the right-turn arrows to the same phase as the non-conflicting left-turn phase on the cross street and the circular indications to the same phase as the adjacent through movement. With the introduction of the flashing yellow arrow, there are numerous possibilities for signaling a right-turn overlap phase. Refer to MUTCD Sections 4D.22 through 4D.24.⁽¹⁾

This type of operation increases efficiency by providing more green time to this right-turn movement, but may compromise the intersection's usability for visually impaired pedestrians. The transition from the protected right-turn movement on the green arrow to the permissive right-turn movement on the circular green masks the sound of the adjacent through vehicles. This makes it difficult for visually impaired pedestrians to hear when the adjacent through vehicles begin to move, which is used as an audible cue for crossing the street. Therefore, the use of accessible pedestrian signals to provide an audible indication of the start of the pedestrian phase may be needed to restore this cue.

Practitioners should note that a right-turn overlap may conflict with drivers making a legal U-turn on the concurrent (and protected) left-turn phase (in other words, both drivers are facing a green arrow for their movement). This conflict can be resolved by either prohibiting drivers from making a U-turn (R3-4, Sec. 2B.18) on that approach or by installing a U-TURN YIELD TO RIGHT TURN sign (R10-16, Sec. 2B.53) near the left-turn signal face.

5.2 VEHICLE AND PEDESTRIAN DISPLAYS

Signal displays can be generally categorized into those for vehicles and those for pedestrians. The following sections discuss each type.

5.2.1 Vehicle Displays

Practitioners should evaluate the location of signal heads based on visibility requirements and type of signal display. While MUTCD requirements govern signal head placement for signal displays (discussed in the previous section), local policies typically determine the specific signal head placement.

When designing signal head placement, practitioners should consider the following in addition to the minimum requirements described in the MUTCD:

- Consistency with other intersections in the area.
- Geometric design issues that could confuse a driver.
- A high percentage of vehicles on one or more approaches that block lines of sight, including trucks and vans.
- The width of the intersection.
- The turning paths of the vehicles.

The 2009 MUTCD recommends that on high-speed approaches (85th percentile greater than 45 mph) or on approaches with three or more through lanes that the primary number of signal displays equal the number of through lanes. These signal displays should be installed over the center of each lane. With the advent of light emitting diode (LED) signal displays, the power requirements for additional signal displays is not significant.

At large signalized intersections, the use of additional signal heads may enhance the safety and operation of the intersection. Exhibit 5-11 shows a typical intersection design with five types of optional heads:

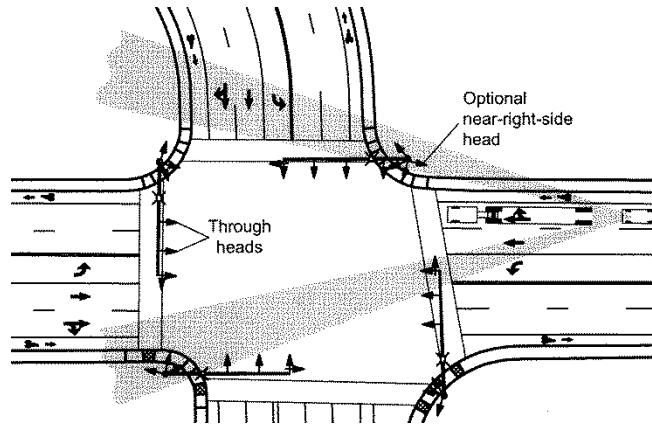
Optional Head #1: A near-right-side head that provides an advanced head at wide intersections as well as a supplemental head for road users unable to see the signal heads over the lanes due to their position behind large vehicles (trucks, etc.).

Optional Head #2: An extra through head that supplements the overhead signal heads. This head provides an indication for vehicles that might be behind large vehicles and may be more visible than the overhead signal head when the sun is near the horizon.

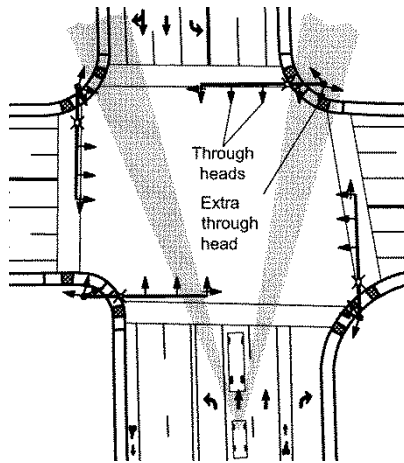
Optional Head #3: An extra left-turn head that guides left-turning vehicles across a wide intersection as they turn. It also improves visibility for vehicles behind large vehicles and for times of day when the sun nears the horizon.

Optional Head #4: A near-left-side head that provides an advance indication a curve in the road upstream of the intersection hampers visibility.

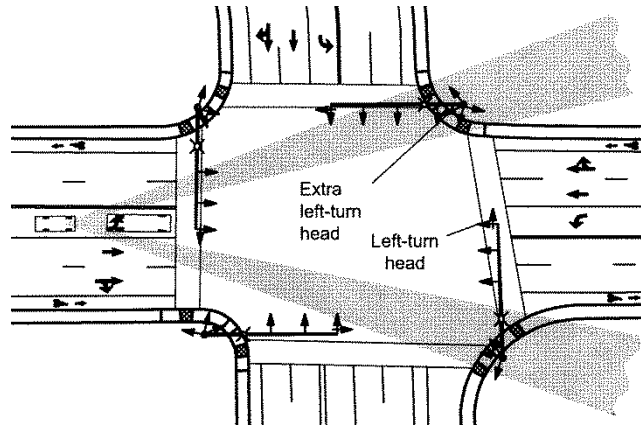
Optional Head #5: This head provides a display in direct view of a right-turn lane and provides a right-turn overlap phase in conjunction with the non-conflicting left-turn phase on the cross street. The head should contain either three circular indications or be a five-section head with three circular indications and two right-turn arrows due to the concurrent pedestrian crossing.



(a) Optional Head #1: Near-side head for through vehicles.

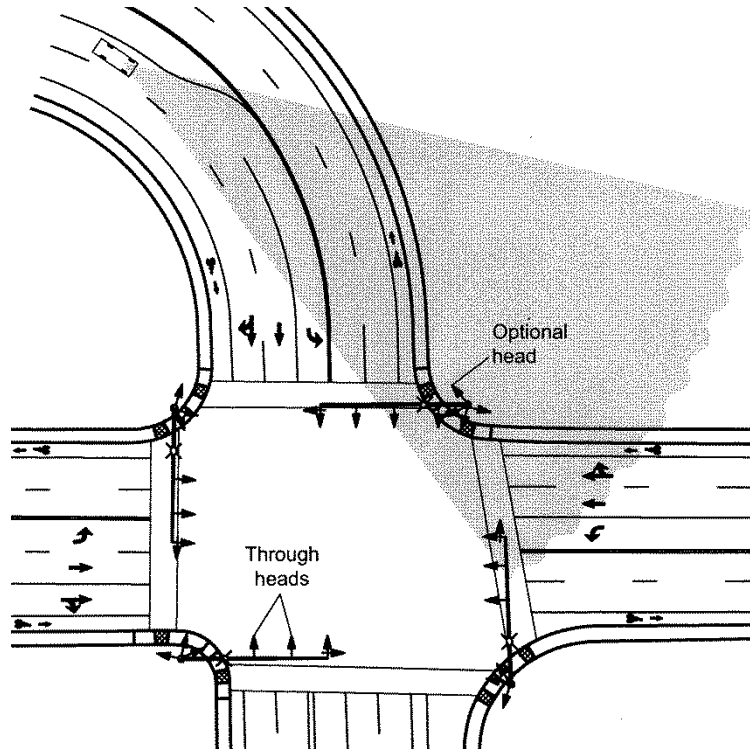


(b) Optional Head #2: Far-side supplemental head for through vehicles.

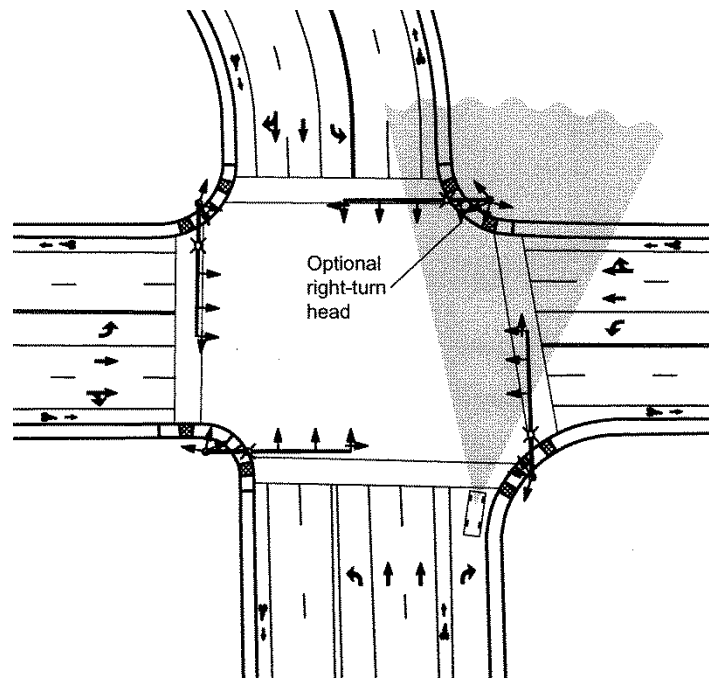


(c) Optional Head #3: Far-side supplemental head for left-turning vehicles.

Exhibit 5-11. Examples showing five optional signal head locations.



(d) Optional Head #4: Near-side head on curving approach.



(e) Optional Head #5: Far-side head for right-turning vehicles.

Exhibit 5-11 (cont'd). Examples showing five optional signal head locations.

5.2.2 Pedestrian Displays

According to section 4E.03 of the 2009 MUTCD, pedestrian signal heads shall be used in conjunction with vehicular traffic control signals under any of the following conditions:⁽¹⁾

- If a traffic control signal is justified by an engineering study and meets Warrant 4, Pedestrian Volume, or Warrant 5, School Crossing (see MUTCD Chapter 4C).
- If an exclusive signal phase is provided or made available for pedestrian movements in one or more directions, with all conflicting vehicular movements being stopped.
- At an established school crossing at any signalized location.
- Where engineering judgment determines that multiphase signal indications (as with split-phase timing) would tend to confuse or cause conflicts with pedestrians using a crosswalk guided only by vehicular signal indications.

Pedestrian signals should be used under the following conditions:

- If it is necessary to assist pedestrians in making a reasonably safe crossing or if engineering judgment determines that pedestrian signal heads are justified to minimize vehicle-pedestrian conflicts.
- If pedestrians are permitted to cross a portion of a street – such as to or from a median of sufficient width for pedestrians to wait – during a particular interval but are not permitted to cross the remainder of the street during any part of the same interval.
- If no vehicular signal indications are visible to pedestrians, or if the vehicular signal indications that are visible to pedestrians starting or continuing a crossing provide insufficient guidance for them to decide when it is reasonably safe to cross, such as on one-way streets, at T-intersections, or at multiphase signal operations.

The MUTCD provides specific guidance on the type and size of pedestrian signal indications (Section 4E.04). As noted in the MUTCD, all new pedestrian signals shall use the UPRAISED HAND (symbolizing DON'T WALK) and WALKING PERSON (symbolizing WALK) indications, shown in Exhibit 5-12. The pedestrian displays shall be mounted so that the bottom of the pedestrian signal display housing (including mounting brackets) is no less than 7 ft and no more than 10 ft above sidewalk level.⁽¹⁾

The 2009 MUTCD approves the use of pedestrian countdown displays. The countdown displays the number of seconds remaining in the pedestrian change interval. Section 4E.07 of the MUTCD requires them to be used on all crosswalks where the pedestrian change interval is more than 7 seconds.

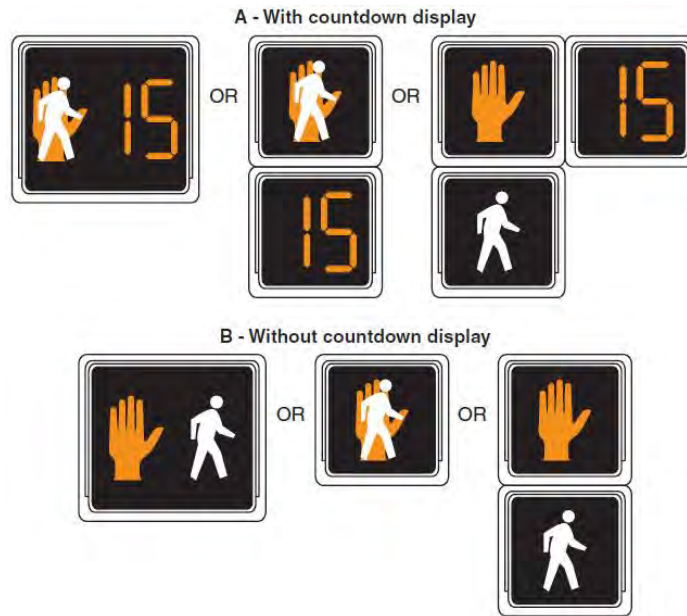


Exhibit 5-12. Pedestrian signal indications.
Source: 2009 MUTCD

Some signalized intersections have factors that may make them difficult for pedestrians who have visual disabilities to cross safely and effectively. As noted in the MUTCD (Section 4E.09), these factors include:⁽¹⁾

- Increasingly quiet cars.
- Right-turn overlaps (which mask the sound of the beginning of the through phase).
- Continuous right-turn movements.
- Complex signal operations (e.g., protected-permissive phasing, lead-lag phasing, or atypical phasing sequences).
- Wide streets.
- Unusual intersection geometrics.

To address these challenges, accessible pedestrian signals have been developed to provide information to the pedestrian in a nonvisual format, such as audible tones, verbal messages, and/or vibrating surfaces. Details on these treatments can be found in the MUTCD⁽¹⁾ and in several references sponsored by the U.S. Access Board and the National Cooperative Highway Research Program (NCHRP).^{(59), (60), (61)}

5.2.3 Pedestrian Hybrid Beacons

The 2009 edition of the MUTCD approved the optional use of pedestrian hybrid beacons (PHB) as a traffic control device. A pedestrian hybrid beacon is a special type of traffic control device used to warn and control traffic at an unsignalized location to assist pedestrians in crossing a street or highway at a marked crosswalk. Chapter 4F of the MUTCD describes the design and operation of these devices in more detail. The PHB in the MUTCD is based on a design previously known as a HAWK signal, developed in Tucson, Arizona.



Exhibit 5-13. Pedestrian hybrid beacon.
Source: FHWA Office of Safety

Although the PHB has been technically defined as a beacon and not a traffic signal, it may still require enabling legislation, which depends directly on a given State's laws concerning signals and what motorists are expected to do when approaching a "dark" signal. Many States require drivers to come to a full and complete stop at a dark signal. The presumption is that in this case, there has been a power outage at the intersection. However, in most States, a dark beacon does not require a motorist to stop, nor would a dark PHB.

The sequence of the PHB is illustrated in Exhibit 5-15.

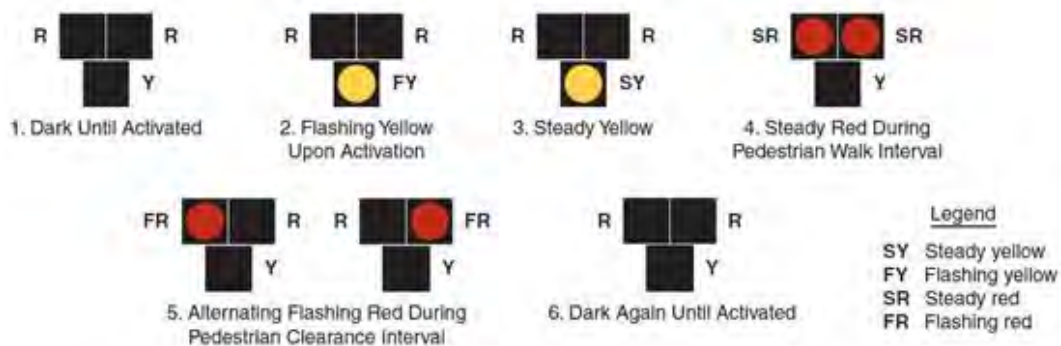


Exhibit 5-14. Sequence for a PHB.
Source: 2009 MUTCD

5.3 TRAFFIC SIGNAL POLE LAYOUT

Three primary types of signal configurations display vehicle signal indications:

- Mast arms.
- Span-wire configurations. Box span-wire design is preferred to diagonal design for new installation.
- Pedestal or post-mounted signal displays.

Exhibit 5-15 identifies the advantages and disadvantages of each configuration.

Advantages	Disadvantages
Mast arm vehicle signal <ul style="list-style-type: none"> • Provides more precise signal head placement • Lower maintenance costs • Many pole esthetic design options 	<ul style="list-style-type: none"> • More costly than span wire • Mast arm lengths can limit use and be extremely costly for some large intersections
Span wire vehicle signal <ul style="list-style-type: none"> • Can accommodate large intersections • Flexibility in signal head placement • Lower initial cost than mast arms 	<ul style="list-style-type: none"> • Higher maintenance costs • Wind and ice can cause problems • May be considered aesthetically unpleasing • Visibility not as good as a mast arm
Pedestal (post-mounted) vehicle signal <ul style="list-style-type: none"> • Low cost • Less impact on view corridors • Lower maintenance costs • Esthetics • Good for supplemental signals 	<ul style="list-style-type: none"> • Difficult to meet MUTCD visibility requirements, particularly at large signalized intersections

Exhibit 5-15. Advantages and disadvantages of various configurations for displaying vehicle signal indications.

In addition to providing support for the optimal location of vehicle and pedestrian signal indications, signal poles need to be located carefully to address the following issues:

- Pedestrian walkway and ramp locations.
- Pedestrian pushbutton locations, unless separate pushbutton pedestals are provided.
- Clearance from the travel way.
- Available right-of-way and/or public easements.
- Overhead utility conflicts, as most power utilities require at least 10 ft clearance to power lines.
- Underground utilities, as most underground utilities are costly to relocate and therefore will impact the location of signal pole foundations.

The MUTCD,⁽¹⁾ the ADAAG,⁽³⁶⁾ and the AASHTO *Roadside Design Guide*⁽⁶²⁾ all contain guidance regarding the lateral placement of signal supports and cabinets. Generally, signal poles should be placed as far away from the curb as practically possible, not conflict with the pedestrian walking paths, and be located for easy access to the pushbuttons by all pedestrians. In some circumstances, it may be difficult or undesirable to locate a single pole that adequately serves both pedestrian ramps and provides adequate clearances. In these cases, one or more pedestals with the pedestrian signal heads and/or pushbuttons should be considered to ensure visibility of the pedestrian signal heads and accessibility to the pushbuttons.

5.4 TRAFFIC SIGNAL CONTROLLER AND CABINET

The traffic controller is the brain of the intersection. Most of the early electro-mechanical controllers have been replaced by solid state controllers across the country. Solid state controllers consist of the NEMA type controllers, Type 170 controllers, ATC Type 2070 controllers, and Advanced ATC controllers. Modern controllers can perform the basic functions needed at typical signalized intersections and have additional capabilities. These include the ability to communicate with other vendor software using standardized communication protocol called National Transportation Communication for ITS Protocol (NTCIP), ability to provide transit priority, control diamond interchanges, etc.

NEMA TS-1 is the first generation of NEMA controllers using discrete solid state electronics interface to the controller field-wiring back panel. TS-1 defines what the controller must do and defines the interface between the controller and the cabinet. Software is built into the controller and is not accessible by others. The newer version, TS-2, is similar to the TS-1 in the way the functionality is defined. However TS-2 specifies a cabinet bus interface unit (BIU) using RS-485 with Synchronous Data Link Control protocol (SDLC) to connect the controller, malfunction management unit (MMU), the detection system, and the back panel. The use of BIU interface reduces the complexity of signal controller cabinet. There are two types of TS-2 controllers. TS-2 Type 1 controller is a pure TS-2 controller whereas TS-2 Type 2 controller can be retrofitted into a TS-1 cabinet.

About the same time the TS-1 specifications were developed, the California Department of Transportation, City of Los Angeles, New York State Department of Transportation, and FHWA developed an open-architecture microcomputer for traffic control. This architecture facilitated the use of software developed by a third party, and the user has access to the software.

The California Department of Transportation led the development of the ATC Type 2070 architecture due to advancements in communications and processors. Model 2070 employs the open-architecture to facilitate the installation of aftermarket processors and other devices in the controllers. The 2070 controller can be placed either in a cabinet for a Type 170 controller or a NEMA controller with the right modules. Like Type 170 controller, software is provided by a third party.

Finally, the Advanced ATC type controller is the second generation of ATC controller with a single-board computer that provides a standard physical and electrical interface to all the other components in the controller.

5.4.1 Physical Location of Equipment

In locating the controller cabinet, consider the following:

- It should not interfere with sight lines for pedestrians or right-turning vehicles.
- It should be in a location less likely to be struck by an errant vehicle and not impeding pedestrian circulation, including wheelchairs and other devices that assist mobility.
- A technician at the cabinet should be able to see the signal indications for two approaches while standing at the cabinet.
- The cabinet should be located near the power source.
- The cabinet location should afford ready access by operations and maintenance personnel, including consideration for where personnel would park their vehicle.

5.5 DETECTION DEVICES

The detectors (or sensors) inform the signal controller of the presence, movement and/or occupancy of motor vehicles, pedestrians, or bicycles at a defined location: the upstream approach to, or downstream side of, an intersection. The signal controller can then use this information to perform its functions, such as allocate the amount of green time, select timing plans, and order signal phases.

5.5.1 Vehicle Detection

Vehicle detectors typically function as presence, pulse (advanced), or system (data). A detector may have more than one function. The detector location, relative to the intersection, often indicates its primary function: presence detectors are located in close proximity to the stop line; pulse detectors are located upstream, well in advance of the intersection; and system detectors are typically located midblock or just downstream of the intersection.

- *Presence* detectors alert the controller to waiting vehicles during the red interval and calls for additional green time (passage or extension) for moving vehicles during the green interval.
- *Pulse* detectors extend the green signal indication for approaching vehicles. Pulse detectors are often placed on high speed approaches to reduce the risk of motorists encountering a yellow signal indication within the dilemma zone. During the red interval, pulse detection of each vehicle can incrementally adjust green time above the 'minimum green' controller setting to ensure servicing of the developed queue.
- *System* detectors collect data such as speed, volume, occupancy, and/or queue information for the purpose of timing plan selection (when in traffic responsive operation), real-time adaptive control, and timing plan overrides. An example of override activation would be to order a special timing plan to prevent off-ramp, vehicle spillback onto an expressway when the off-ramp, queue detector is occupied.

Detectors are placed either in-roadway or over the roadway surface. The performance of in-roadway detectors such as inductive loops, magnetic, and magnetometer detectors depends upon the quality of the installation, proximity to the vehicle, and the condition of the pavement structure. These detectors are designed to be insensitive to inclement weather but are subject to disruption of service due to pavement milling, utility cuts, and pavement movement. The main disadvantage of in-roadway detection is the disturbance to the roadway surface and exposure of personnel to traffic during installation and maintenance. Over roadway detectors, such as video detection and digital matrix radar, are generally auto-programmable, multi-lane, and multi-functional. Digital matrix radar detectors are insensitive to weather, continuously track vehicles in the zone, and require little maintenance. Factors affecting the performance of video detection are often related to the camera lens and mounting: wind, fog, shadows, occlusion, etc. Newer types of detection feature remote monitoring and troubleshooting. Out of service or unreliable vehicle detection results in unused green time, diminished dilemma zone protection, omitted phases, poor optimization, and driver frustration. The FHWA *Traffic Detector Handbook* includes further discussion on detector technology.

The dilemma zone is that portion of the approach where a driver seeing a yellow indication must make a decision whether to stop safely or to proceed through the intersection. Hence, the minimum stopping distance usually dictates dilemma zone. The actual distances vary by jurisdictional policies. Practitioners should review these policies before designing the traffic signal and detector system. The typical location for advance detectors is based on stopping sight distance, as shown in Exhibit 5-16. The stopping distance can be computed for both the average stopping condition as well as the probability ranges for stopping. For higher speed approaches (45 mph or greater) and to account for the desired probability of stopping, pulse or advanced detection should be used. More detailed information on detector placement, including the results of several calculation methods, can be found in FHWA's *Manual of Traffic Detector Design*.⁽⁵⁸⁾

Exhibit 5-16. Location of advanced vehicle detectors.

Speed	Calculated Stopping Distance	Single Detector Setback	Multiple Detector Setback	
			10% Probability of Stopping	90% Probability of Stopping
20 mph	72.2 ft	70 ft	—	—
25 mph	104.4 ft	105 ft	—	—
30 mph	140.8 ft	140 ft	—	—
35 mph	182.9 ft	185 ft	102 ft	254 ft
40 mph	231.0 ft	230 ft	122 ft	284 ft
45 mph	283.8 ft	*	152 ft	327 ft
50 mph	341.9 ft	*	172 ft	353 ft
55 mph	406.3 ft	*	234 ft	386 ft

* Use multiple detectors or volume-density modules.

Source: Reference 63 (table 4-3); Reference 64 (table 7-1);

Proper settings of the detector equipment can help fine tune operations and safety improvements at a signalized intersection. Both the detection equipment and the traffic signal controller are typically capable of adjusting the outputs from the detector and/or inputs to the controller. A few of the more common programmable features are lock, delay, extend, and switch.

- A **Lock** (Y or N) retains the call placed on the controller during the red signal indication for the phase even though a vehicle moves outside the detection zone. The lock feature is useful on left-turn lanes where a vehicle may creep forward while waiting on the protected left-turn green signal indication.
- A **Delay** (in seconds) can be set on turning lane detection where permissive turns are allowed in order to give vehicles time to select a safe gap to complete their turn, without placing the call to the controller for the protected left turn phase.
- An **Extend** (in seconds) holds the call upon the controller for a defined period of time after the vehicle leaves the zone of detection.
- A **Switch** dynamically changes the assignment of a vehicle detector to a different vehicle phase during a specific portion of the cycle length. For example, a heavy side street volume of left turners might benefit from unused green time from a lighter volume adjacent through movement. Switching moves the detector call from the left-turn phase (phase 7, protected lefts) to the adjacent through movement phase (phase 4, throughs & permissive lefts) during the through movement green time to accommodate more left turners. If switching were not used (as in this example), absent of a vehicle detection for phase 4 or 8 (side street throughs), then the side street protected left-turn phase would max out, cross the barrier, and return to the next phase to be served on the main street (see Exhibit 5-6).

When selecting the type of detection for new signalized intersections or as a replacement for detection at existing signalized intersections, the following considerations may be made:

- Is detection of multiple user groups required (i.e., motorists, pedestrians, motorcycles, etc.)?
- Is the detection proprietary or is it compatible with various/existing interfaces?
- Is the detection reliable and does it have a good reputation?
- What is the expected life of the detection?
- Will the detection require changes in existing infrastructure?

- Does the detection have the capability to be located where its repair will not require interrupting traffic? Are alternatives available that won't require the interruption of traffic flow?
- Will repairs need to be accomplished by contract or in-house?
- How do environmental conditions affect the detection (e.g., wind, ice, glare, occlusion, shadowing, and fog may limit the capabilities of some video and above-roadway detection)? Is there potential for accelerated wear and tear of equipment due to weather (freeze, thaw, heat) or pavement movement or failure?
- Does the detection have other capabilities aside from traffic detection (i.e., volume and classification counts, occupancy, etc.)? Compared with other methods of data collection, is this method reliable?
- What is the fail-safe condition for detected fault? Does the system have a diagnostic or alert system due to fault?
- If in-roadway detection is used, in what type of surface will the detection be installed (i.e., concrete, old asphalt, gravel, etc.)? Will future pavement surface maintenance affect its operation, temporarily (work zone during construction) or permanently?
- Will the detection require boring or trenching?
- What are the initial and lifecycle costs? Does the detection have ongoing regular maintenance costs?
- Do the detector equipment specifications match the stated operational and safety needs?

5.5.2 Pedestrian Detection

Pedestrian detection at actuated signals is typically accomplished through the use of pedestrian push buttons. Accessible pedestrian signal detectors, or devices to help pedestrians with visual or mobility impairments activate the pedestrian phase, may be pushbuttons or other passive detection devices. For pushbuttons to be accessible, they should be placed in accordance with the guidance in the MUTCD (Sections 4E.08, 4E.09).⁽¹⁾

- Unobstructed and adjacent to a level all-weather surface to provide access by a wheelchair with a wheelchair-accessible route to the ramp.
- Within 5 ft of the crosswalk extended.
- If possible, between 1.5 and 6 ft from edge of curb. If physical constraints make this impractical, locate no more than 10 ft off the edge of the curb, shoulder, or pavement.
- Parallel to the crosswalk to be used.
- Separated from other pushbuttons by a distance of at least 10 ft.
- Mounted at a height of at least 3.5 ft and no more than 4.0 ft above the sidewalk.

Types of passive detection devices include, but are not limited to, video and infrared camera systems. Pedestrian detection can be helpful for assigning right-of-way when installed at locations with high demands of both pedestrian and vehicle volumes. As one form of transportation demand increases over another, the detection can instruct the signal controller to give precedence to the higher demand. Pedestrian detection may also allow for detection of users that will require extended walk times. Alternative methods of pedestrian detection, including infrared and microwave detectors, are emerging. Additional information on these devices can be found in FHWA's *Pedestrian Facilities User Guide—Providing Safety and Mobility*.⁽³⁸⁾

5.6 TRAFFIC SIGNAL CONTROL TYPE

Traffic signals operate in pre-timed, semi-actuated, or actuated mode based on the presence and operations of detectors. Pre-timed signals operate with fixed cycle lengths and green splits, and in turn can operate either in isolation or coordination with adjacent traffic signals. Pre-timed coordinated signals can feature multiple timing plans with different cycle, split, and offset values for different periods of the day. Pre-timed control is ideally suited to closely spaced intersections where traffic volumes and patterns are relatively consistent on a daily or day-of-week basis.⁽⁶⁶⁾

Actuated signals vary the amount of green time allocated to each phase based on traffic demand; these signals can operate either in a fully actuated or semi-actuated mode. Actuated control provides variable lengths of green timing for phases that are equipped with detectors. The time for each movement depends on the characteristics of the intersection and timing parameters which are based on demand at the intersection.

An intersection that is fully actuated does not have a fixed cycle length; the durations of all phases are dependent on either vehicle actuations on their approaches or on maximum green times. An intersection that is under semi-actuated control typically has detectors on the minor street and on the major street left turns, but not on the major street through movements. The signal controller dwells or rests in the major street through phases and services the minor movements (i.e., minor streets and major street left-turns) upon demand. The intersection does not have a fixed cycle length.

An actuated signal can also work in coordination with other nearby traffic signals. A coordinated signal with actuated phases (actuated-coordinated) operates similarly to an intersection under semi-actuated control. The major street through phases are usually not actuated, the minor movements (including major street left turns) are actuated, and the intersection operates with a fixed cycle length. By fixing the major street movements, the coordination creates a “green band” for traffic to move smoothly through multiple adjacent intersections. This green band can be increased if unused green time is available from the other movements; it can be given to the major street through movement to further improve coordination. This unused time can also be shared with other movements as desired by the practitioner.

Some agencies have implemented more advanced traffic control plans using additional detection or adaptive control plans. Traffic responsive systems typically include additional “system detectors” between signals to provide more information to the system. Volume thresholds for a set of sensors are pre-determined by the traffic engineer to invoke specific cycles, splits, and offset combinations. This information can be used to help the controller choose the most appropriate plans for the current situations. Adaptive control has been used to improve traffic congestion and reduce delay using conventional signal control systems. Adaptive signal control technology continuously adjusts the signal timing (including modifying cycle lengths) beyond what is done by fully actuated or actuated-coordinated control by responding to changing traffic patterns. Adaptive control can distribute green times equitably to all traffic movements, improve travel time reliability and prolong the effectiveness of a traffic signal timing plan.

5.7 BASIC SIGNAL TIMING PARAMETERS

Signal operation and timing have a significant impact on intersection performance. Controllers have a vast array of inputs that permit tailoring of controller operation to the specific intersection. This section provides guidance for determining basic timing parameters.

The development of a signal timing plan should address all user needs at a particular location, including pedestrians, bicyclists, transit vehicles, emergency vehicles, automobiles, and trucks. For the purposes of this section, signal timing is divided into two elements: pedestrian timing and vehicle timing.

5.7.1 Vehicle Timing—Green Interval

Ideally, the length of the green display should be sufficient to serve the demand present at the start of the green phase for each movement and should be able to move groups of vehicles, or platoons, in a coordinated system. At an actuated intersection, the length of the green interval varies based on inputs received from the detectors. Minimum and maximum green times for each phase are assigned to a controller to provide a range of allowable green times. Detectors are used to measure the amount of traffic and determine the required time for each movement within the allowable range.

In pre-timed operations, minimum green and maximum green are equal. The green interval should meet the driver expectancy requirements, pedestrian requirements, and the requirements to clear the expected queue at the stop line. When the detector is at the stop line, the minimum green time should meet driver expectancy requirements and pedestrian requirements.⁽¹⁾ The minimum green is generally set to approximately 5 to 15 seconds based on the type of street and the type of movement to meet driver expectancy.

When the detector is located upstream of the stop line, the minimum green must meet the additional requirement to clear the vehicles queued between the stop line and the detector nearest the stop line. Consider an intersection with the following properties: average vehicle spacing is 25 ft per vehicle, initial start-up time is 2 s, and vehicle headway is 2 s per vehicle. For an approach with a detector located 100 ft from the stop line, the minimum green time is $2 + (100 \text{ ft} / 25 \text{ ft} \times 2) = 10 \text{ s}$.

The maximum green time is the maximum limit to which the green time can be extended for a phase in the presence of a call from a conflicting phase. Exhibit 5-17 illustrates the functionality of maximum green timer. The maximum green timer begins when a call is placed on a conflicting phase. The phase is said to "max-out" if the maximum green time is reached even if actuations have been received that would typically extend the phase.

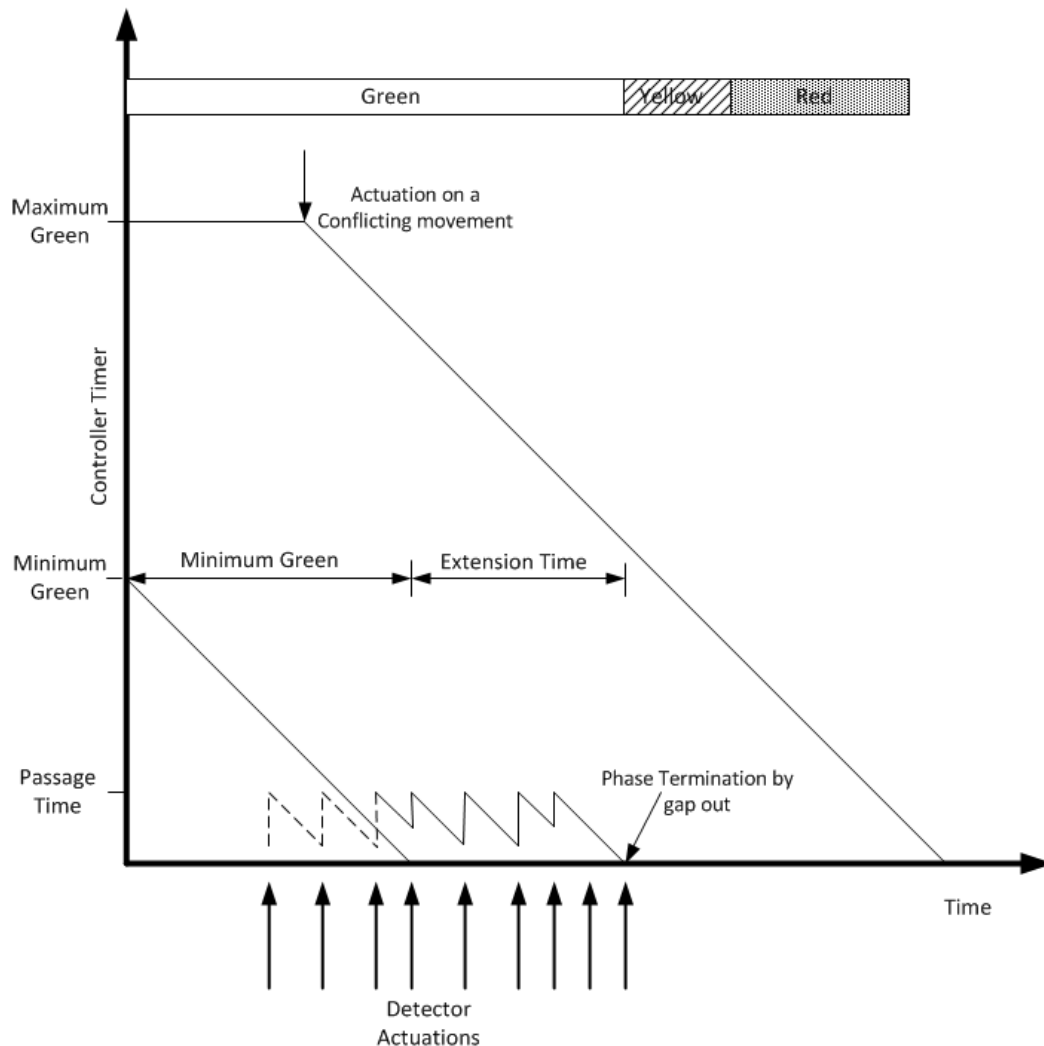


Exhibit 5-17. Illustration of maximum green functionality.

5.7.2 Vehicle Timing—Detector Inputs

One advantage of actuated control is its capacity to adjust timing parameters based on vehicle or pedestrian demand. The detectors and the timing parameters allow the signal to respond to varied flow throughout the day. For pedestrians, detectors are located for convenient access; for vehicles, detector spacing is a function of travel speed and the characteristics of the street. The operation of the signal is highly dependent on detector inputs. More information about detector features and settings for various detector configurations can be found in the FHWA *Traffic Detector Handbook*.⁽⁶³⁾

Volume-density timing is used to improve the efficiency of intersection operation. A gap-reduction feature called *variable initial* is used to improve intersection efficiency on approaches where the detectors are not at the stop line (presence detection) but a distance upstream of the stop line (advance or pulse detection). Variable initial, as illustrated in Exhibit 5-18, alleviates the need to provide a large minimum green to clear all vehicles stored between the stop line and the detector and thus improves intersection efficiency during low volume conditions. Another volume density feature called gap reduction uses gap timers to reduce the allowable gap time the longer the signal is green. This type of timing makes the signal less likely to extend the green phase the longer the signal is green. A typical setting for a volume-density controller is to have the passage

gap set to twice the calculated gap time to ensure the phase does not gap out too early. The minimum gap time might be set to less than the calculated gap time on multiple lane approaches, depending on the characteristics of the intersection.

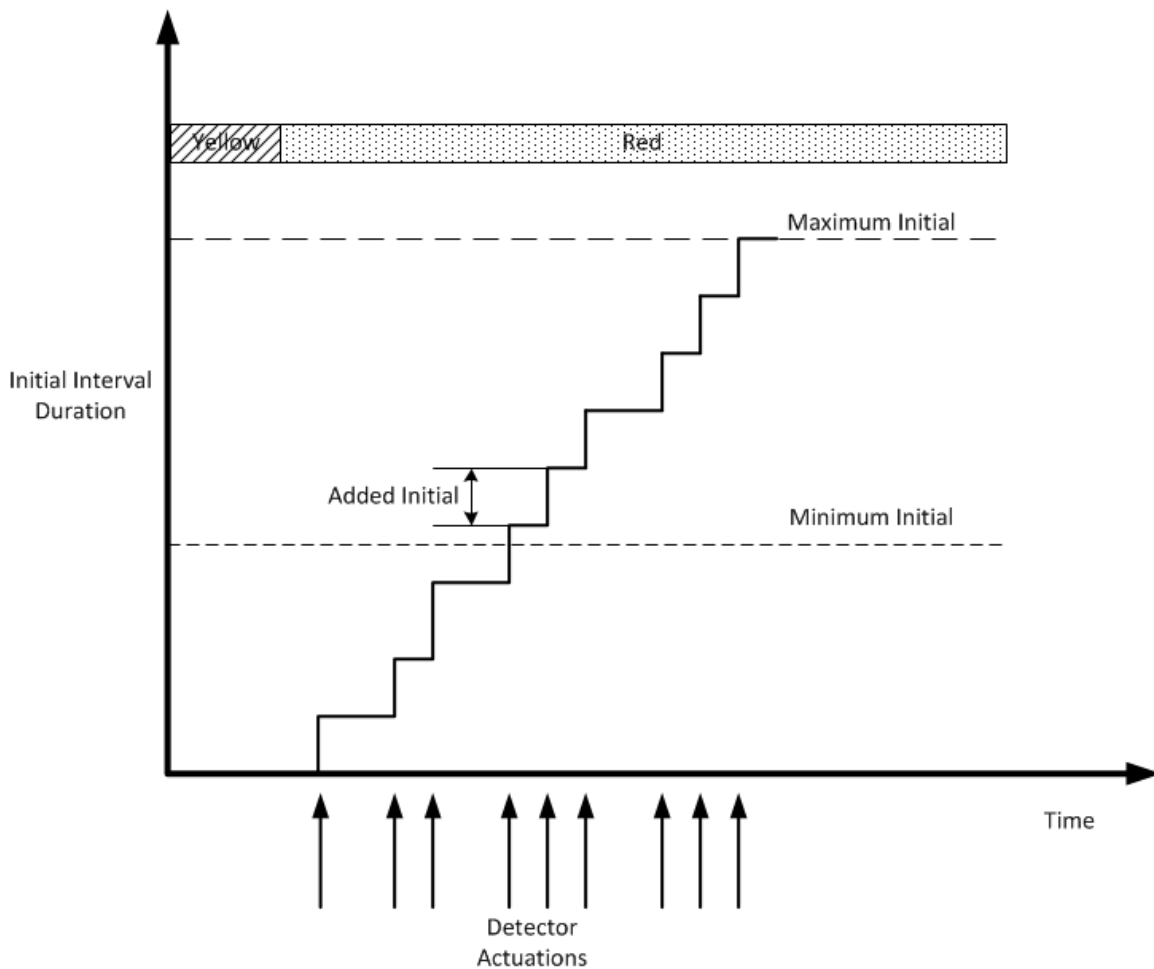


Exhibit 5-18. Illustration of variable initial feature.

Signal timing parameters may provide an opportunity to maximize the efficiency of the intersection. Signal timing parameters control how quickly the phase ends once traffic demand is no longer present. When coordination timings are used, the unused green time can be assigned to the coordinated phase or divided amongst the other phases, but should not exceed the split time.

5.7.3 Vehicle Timing—Vehicle Clearance

The vehicle clearance interval consists of the yellow change and red clearance intervals. The recommended practice for computing the vehicle clearance interval is the ITE formula (reference 56, equation 11-4), given in equation 2 (to use with metric inputs, use 1 m = 0.3048 ft):

$$CP = t + \frac{V}{2a + 64.4g} + \frac{W + L}{V} \quad (\text{U.S. Customary})$$

where: CP = change period (s)
 t = perception-reaction time of the motorist (s); typically 1
 V = speed of the approaching vehicle (ft/s)
 a = comfortable deceleration rate of the vehicle (ft/s²); typically 10 ft/s²
 W = width of the intersection, curb to curb (ft)
 L = length of vehicle (ft); typically 20 ft
 g = grade of the intersection approach (%); positive for upgrade, negative for downgrade

For change periods longer than 5 seconds, a red clearance interval is typically used. Some agencies use the value of the third term as a red clearance interval. The MUTCD does not require specific yellow or red intervals, but provides guidance that the yellow change interval should be approximately 3 to 6 seconds and that in most cases the red clearance interval should not exceed 6 seconds (Section 4D.26).⁽¹⁾ Note that because high-volume signalized intersections tend to be large and frequently on higher speed facilities, their clearance intervals are typically on the high end of the range. These longer clearance intervals increase loss time at the intersection and thus reduce capacity.

The topic of yellow and red clearance intervals has been much debated in the traffic engineering profession. At some locations, the yellow clearance interval is either too short or set improperly due to changes in posted speed limits or 85th percentile speeds. This is a common problem and frequently causes drivers to brake hard or to run through the intersection during the red phase. Because not all States follow the same law with regard to what is defined as "being in the intersection on the red phase," local practice for defining the yellow interval varies considerably.

Longer clearance intervals may cause drivers to enter the intersection later, breeding disrespect for the traffic signal. Wortman and Fox conducted a study that showed that the time of entry of vehicles into the intersection increased due to a longer yellow interval.⁽⁶⁷⁾ NCHRP 705 showed mixed results for the extension of the yellow change interval and the yellow/red change interval. It showed positive results on all crash types when the red change interval was extended.

5.7.4 Pedestrian Timing

Pedestrian timing requirements include a WALK interval and a pedestrian change (flashing upraised hand) interval. The WALK interval varies based upon local agency policy. The MUTCD recommends a minimum WALK time of 7 seconds, although WALK times as low as 4 seconds may be used if pedestrian volumes and characteristics do not require a 7-second interval (section 4E.06).⁽¹⁾ The WALK interval gives pedestrians adequate time to perceive the WALK indication and depart the curb before the pedestrian change (flashing upraised hand) interval begins.

In downtown areas, longer WALK times are often appropriate to promote walking and serve pedestrian demand. School zones and areas with large numbers of elderly pedestrians also warrant consideration and the display of WALK times in excess of the minimum WALK time.

The MUTCD states that the pedestrian clearance time should allow a pedestrian crossing in the crosswalk to leave the curb and travel to at least the far side of the traveled way or to a median of sufficient width for pedestrians to wait. The MUTCD uses a walk speed of 3.5 ft/s for determining crossing times.^(Error! Bookmark not defined.) However, FHWA pedestrian design guidance

recommends a lower speed if needed to accommodate users who require additional time to cross the roadway, and in particular a lower speed in areas where there are concentrations of children and or elderly persons. Pedestrian clearance time is calculated using equation 1:

$$\text{Pedestrian Clearance Time} = \frac{\text{Crossing Distance}}{\text{Walking Speed}}$$

where: Pedestrian Clearance Time is in seconds
 Crossing Distance is measured from the near curb to at least the far side of the traveled way or to a median; and
 Walking Speed is 3.5 ft/s as indicated above.

Pedestrian clearance time is accommodated during either a combination of pedestrian change (upraised hand) interval time and yellow change and red clearance time or by pedestrian change (upraised hand) interval time alone. At high-volume locations, it may be necessary as a tradeoff for vehicular capacity to use the yellow change interval as part of satisfying the calculated pedestrian clearance time. According to the 2009 MUTCD,⁽¹⁾ a buffer interval illustrating a steady UPRaised HAND symbolizing DON'T WALK shall be displayed following the pedestrian change interval for at least 3 seconds prior to the release of any conflicting vehicular movement. The pedestrian intervals are illustrated in Exhibit 5-19.

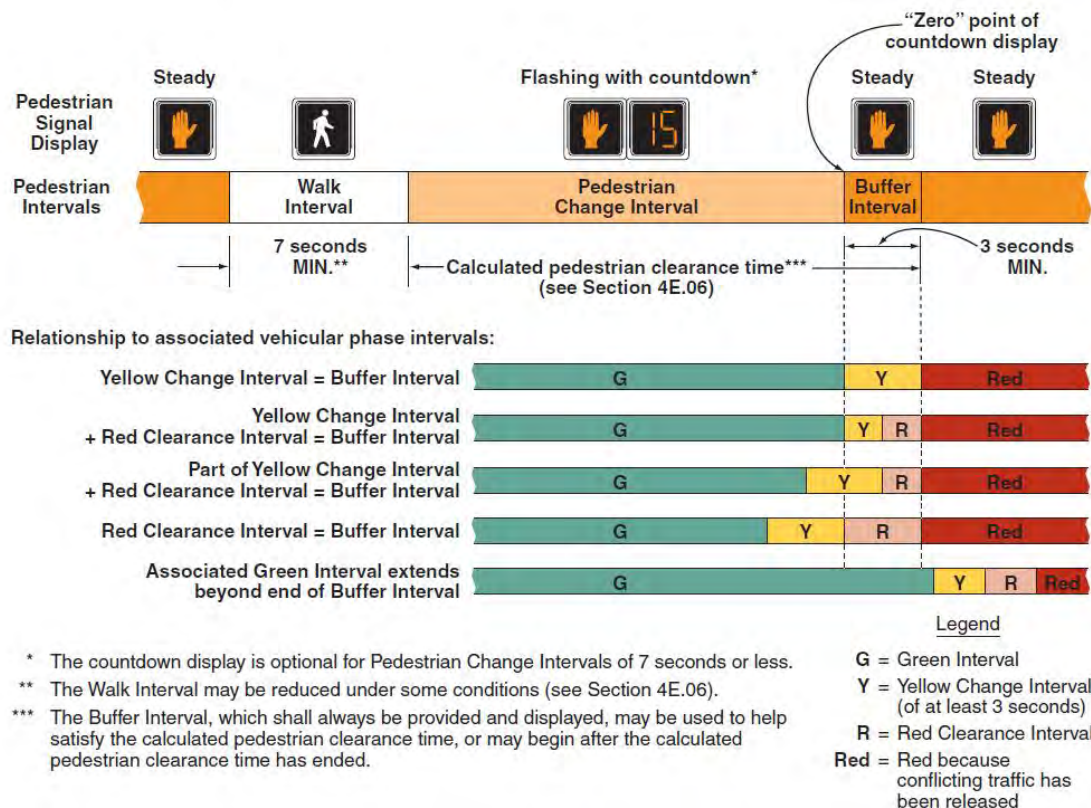


Exhibit 5-19. Pedestrian intervals.
 Source: 2009 MUTCD

Practitioners should also consider the impact of longer pedestrian intervals on vehicular green time and overall cycle lengths. Consideration should be given to the volume of pedestrians, the pedestrian walk speed used to calculate the pedestrian interval, and the volume and turn movements of vehicular traffic.

5.7.5 Vehicle Timing—Cycle Length

For isolated, actuated intersections, cycle length varies from cycle to cycle based on traffic demand and signal timing parameters. For coordinated intersections, a background cycle length is used to achieve consistent operation between consecutive intersections. In general, shorter cycle lengths are preferable to longer ones because they result in less delay and shorter queues. However, the need to accommodate multiple pedestrian movements across wide roadways, coupled with complex signal phasing and minimum green requirements to accommodate signal progression in multiple directions, may sometimes require the use of even longer cycle lengths. Wherever possible, such use should be limited to peak traffic periods only.

In general, cycle lengths for conventional, four-legged intersections should not exceed 120 seconds, although larger intersections may require longer cycle lengths of 140 to 150 seconds. Some busy intersections even operate at 180-second cycle lengths. Longer cycle lengths generally result in increased delay and queues to all users, particularly minor movements.

5.8 SIGNING AND PAVEMENT MARKING DESIGN

Signs and pavement markings are important elements of signalized intersection design. Because of the complexity of driver decisions, particularly at large signalized intersections, special attention to signing and pavement markings can maximize the safety and efficiency of the intersection. At signalized intersections, these traffic control devices serve several key functions, including:

- Advance notice of the intersection.
- Directional route guidance.
- Lane use control, including indications of permissive or prohibited turning movements.
- Regulatory control of channelized right turn movements (e.g., through the use of YIELD signs).
- Delineation and warning of pedestrian crossing locations.
- Delineation and warning of bicycle lane locations.

The MUTCD is the primary reference for use in the design and placement of signs and pavement markings.⁽¹⁾ Additional resources include State supplements to the MUTCD and reference materials such as ITE's *Traffic Control Devices Handbook* (TCDH)⁽⁶⁸⁾ and *Traffic Signing Handbook*.⁽⁶⁹⁾

Designing effective signing and pavement markings, particularly at high-volume signalized intersections, often requires thinking beyond standard drawings of typical sign and pavement marking layouts at intersections. High-volume signalized intersections typically have more lanes than most intersections. They may have redirected or restricted turning movements. They often join two or more designated routes (e.g., State highways) that require directional guidance to the user. They also are frequently located in urban areas where other intersections, driveways, and urban land use create visibility conflicts. The following questions, adapted from the ITE *Traffic Signing Handbook*,⁽⁶⁹⁾ represent a basic thought process recommended for engineers to follow when developing a sign layout at an intersection:

1. **From a given lateral and longitudinal position on the roadway, what information does the user need, both in advance and at the intersection?** At signalized intersections, is information on lane use provided at the intersection? Is advance street name information ("XX Street, Next Signal," etc.) and (if appropriate) route number directional signing provided in advance of the intersection? Exhibit 5-20 gives an example of an advance sign that provides street names for the next two signalized intersections.



Exhibit 5-20. Example of advance street name sign for two closely spaced intersections.

2. **Are there any on- or off-road conditions that would violate driver expectancy?** Lane drops and right-hand exits for left turns are both examples where driver expectancy is violated and should be addressed with signing. Exhibit 5-21 shows an example of signing used to advise motorists of a dropped lane at an upcoming intersection.



Exhibit 5-21. Example of signing for a left-hand lane drop.

3. **Is a specific action required by a road user?** If the road user needs to be in an appropriate lane in advance of an intersection to make a movement at the intersection, signing and corresponding pavement markings should convey this message to the user. Exhibit 5-22

provides an example of overhead signs and pavement markings used to assist drivers in selecting the proper lane on the approach to a signalized intersection.



Exhibit 5-22. Example of advance overhead signs and pavement markings indicating lane use for various destinations.

4. **Are signs located so that the road user will be able to see, comprehend, and attend to the intended message?** Signs must be simple enough to easily comprehend and attend to before the driver receives the next message. This requires adequate sign size, sign spacing, and attention to the number of elements on each sign. Additional signing enhancements, consistent with the principles of sign and message spreading (separating overlapping or numerous route signs onto two installations to improve comprehension and readability), may include the use of overhead signs in advance of large intersections and/or large retro-reflectORIZED or internally illuminated overhead signs (including street name signs) at the intersections.
5. **For what part of the driver population is the sign being designed?** Have the needs of older drivers or nonlocal drivers been accommodated? This may require the use of larger lettering or sign illumination.
6. **Does the sign “fit in” as part of the overall sign system?** Signing at an intersection needs to be consistent with the overall sign layout of the connecting road system. For example, the consistent use of guide signs is helpful to freeway users in identifying the appropriate exit. Similar consistency is needed on arterial streets with signalized intersections.

Pavement markings also convey important guidance, warnings, and regulatory lane-use information to users at signalized intersections. In addition to delineating lanes and lane use, pavement markings clearly identify pedestrian crossing areas, bike lanes, and other areas where driver attention is especially important. Where in-pavement detection is installed for bicycles and motorcycles, appropriate markings should be painted to guide these vehicles over the portion of the loop that will best detect them.

Several supplemental pavement markings are particularly useful at large signalized intersections. For example, the use of lane line extensions (dotted white lines) into the intersection can be a helpful tool where the intersection is so large that the alignment of through

or turning lanes between entering the intersection and exiting the intersection could be confused. This can occur, for example, where multiple turn lanes are provided, where the through lane alignments make a curve through the intersection, or where the receiving lanes at an intersection are offset laterally from the approach lanes. In addition, pavement legends indicating route numbers and/or destinations in advance of the intersection (i.e., “horizontal signing”) may be used to supplement signing for this purpose, as shown in Exhibit 5-23.



Exhibit 5-23. Example of pavement legends indicating destination route numbers (“horizontal signing”).

5.9 ILLUMINATION DESIGN

As noted in the *American National Standard Practice for Roadway Lighting (RP-8-00)*, “[t]he principal purpose of roadway lighting is to produce quick, accurate, and comfortable visibility at night. These qualities of visibility may safeguard, facilitate, and encourage vehicular and pedestrian traffic... [T]he proper use of roadway lighting as an operative tool provides economic and social benefits to the public including:

- (a) Reduction in night accidents, attendant human misery, and economic loss.
- (b) Aid to police protection and enhanced sense of personal security.
- (c) Facilitation of traffic flow.
- (d) Promotion of business and the use of public facilities during the night hours.⁽⁷⁰⁾

Specifically with respect to intersections, the document notes that “[s]everal studies have identified that the primary benefits produced by lighting of intersections along major streets is the reduction in night pedestrian, bicycle and fixed object accidents” (Section 3.6.2).⁽⁷⁰⁾ With respect to signalized intersections, roadway lighting can play an important role in enabling the intersection to operate at its best efficiency and safety. The highest traffic flows of the day (typically the evening peak period) may occur during dusk or night conditions where lighting is critically important, particularly in winter for North American cities in northern latitudes.

The document includes three different criteria for roadway lighting: illuminance, luminance, and small target visibility (STV). These are described as follows:

- Illuminance is the amount of light incident on the pavement surface from the lighting source.

- Luminance is the amount of light reflected from the pavement toward the driver's eyes. The luminance criterion requires more extensive evaluation. Because the reflectivity of the pavement surfaces constantly changes over time, it is difficult to accurately estimate this criterion.
- Small target visibility is the level of visibility of an array of targets on the roadway. The STV value is determined by the average of three components: the luminance of the targets and background, the adaptation level of adjacent surroundings, and the disability glare.

5.9.1 Illuminance

The two principal measures used in the illuminance method are light level and uniformity ratio. Light level represents the intensity of light output on the pavement surface and is reported in units of lux (metric) or footcandles (U.S. Customary). Uniformity represents the ratio of either the average-to-minimum light level (E_{avg}/E_{min}) or the maximum-to-minimum light level (E_{max}/E_{min}) on the pavement surface. The light level and uniformity requirements are dependent on the roadway classification and the level of pedestrian night activity.

The basic principle behind intersection lighting is that the amount of light on the intersection should be proportional to the classification of the intersecting streets and equal to the sum of the values used for each separate street. For example, if Street A is illuminated at a level of x and Street B is illuminated at a level of y , the intersection of the two streets should be illuminated at a level of $x+y$. RP-8-00 also specifies that if an intersecting roadway is illuminated above the recommended value, then the intersection illuminance value should be proportionately increased. If the intersection streets are not continuously lighted, a partial lighting system can be used. RP-8-00 and its annexes should be reviewed for more specific guidance on partial lighting, the specific calculation methods for determining illuminance, and guidance on the luminance and STV methods.⁽⁷⁰⁾

Exhibit 5-24 presents the recommended illuminance for the intersections within the scope of this document located on continuously illuminated streets. Separate values have been provided for portland cement concrete road surfaces (RP-8-00 Road Surface Classification R1) and typical asphalt concrete road surfaces (RP-8-00 Road Surface Classification R2/R3).

Exhibit 5-25 presents the roadway and pedestrian area classifications used for determining the appropriate illuminance levels in exhibit 5-26. RP-8-00 clarifies that although the definitions given in exhibit 5-25 may be used and defined differently by other documents, zoning bylaws, and agencies, the area or roadway used for illumination calculations should best fit the descriptions contained in exhibit 5-25 (section 2.0, p. 3).⁽⁷⁰⁾

5.9.2 Veiling Luminance

Stray light from light sources within the field of view produces veiled luminance. This stray light is superimposed in the eye on top of the retinal image of the object of interest, which alters the apparent brightness of that object and the background in which it is viewed. This glare, known as disability glare, reduces a person's visual performance and thus must be considered in the design of illumination on a roadway or intersection.⁽⁷⁰⁾ Exhibit 5-24 shows the maximum veiling luminance required for good intersection lighting design.

Exhibit 5-24. Recommended illuminance for the intersection of continuously lighted urban streets.

Pavement Classification ¹	Roadway Classification	Average Maintained Illuminance at Pavement			Uniformity Ratio (Eavg/Emin) ³	Veiling Luminance Ratio (Lvmax/Lavg) ⁴
		Pedestrian/Area Classification				
		High (lux (fc) ²)	Medium (lux (fc) ²)	Low (lux (fc) ²)		
R1	Major/Major	24.0 (2.4)	18.0 (1.8)	12.0 (1.2)	3.0	0.3
	Major/Collector	20.0 (2.0)	15.0 (1.5)	10.0 (1.0)	3.0	0.3
	Major/Local	18.0 (1.8)	14.0 (1.4)	9.0 (0.9)	3.0	0.3
	Collector/Collector	16.0 (1.6)	12.0 (1.2)	8.0 (0.8)	4.0	0.4
	Collector/Local	14.0 (1.4)	11.0 (1.1)	7.0 (0.7)	4.0	0.4
	Local/Local	12.0 (1.2)	10.0 (1.0)	6.0 (0.6)	6.0	0.4
R2/R3	Major/Major	34.0 (3.4)	26.0 (2.6)	18.0 (1.8)	3.0	0.3
	Major/Collector	29.0 (2.9)	22.0 (2.2)	15.0 (1.5)	3.0	0.3
	Major/Local	26.0 (2.6)	20.0 (2.0)	13.0 (1.3)	3.0	0.3
	Collector/Collector	24.0 (2.4)	18.0 (1.8)	12.0 (1.2)	4.0	0.4
	Collector/Local	21.0 (2.1)	16.0 (1.6)	10.0 (1.0)	4.0	0.4
	Local/Local	18.0 (1.8)	14.0 (1.4)	8.0 (0.8)	6.0	0.4

¹ R1 is typical for portland cement concrete surface; R2/R3 is typical for asphalt surface.

² fc = footcandles

³ Eavg/Emin = Average illuminance divided by minimum illuminance

⁴ Lvmax/Lavg = Maximum veiling luminance divided by average luminance.

Source: Reference 70, table 9 (for R2/R3 values); R1 values adapted from table 2.

Exhibit 5-25. RP-8-00 guidance for roadway and pedestrian/area classification for purposes of determining intersection illumination levels.

Roadway Classification	Description	Average Daily Vehicular Traffic Volumes (ADT) ¹
Major	That part of the roadway system that serves as the principal network for through-traffic flow. The routes connect areas of principal traffic generation and important rural roadways leaving the city. Also often known as "arterials," thoroughfares," or "preferentials."	More than 3,500
Collector	Roadways servicing traffic between major and local streets. These are streets used mainly for traffic movements within residential, commercial, and industrial areas. They do not handle long, through trips.	1,500 to 3,500
Local	Local streets are used primarily for direct access to residential, commercial, industrial, or other abutting property.	100 to 1,500

Pedestrian Conflict Area Classification	Description	Possible Guidance on Pedestrian Traffic Volumes ²
High	Areas with significant numbers of pedestrians expected to be on the sidewalks or crossing the streets during darkness. Examples are downtown retail areas, near theaters, concert halls, stadiums, and transit terminals.	More than 100 pedestrians/hour
Medium	Areas where lesser numbers of pedestrians use the streets at night. Typical are downtown office areas, blocks with libraries, apartments, neighborhood shopping, industrial, older city areas, and streets with transit lines.	11 to 100 pedestrians/hour
Low	Areas with very low volumes of night pedestrian usage. These can occur in any of the cited roadway classifications but may be typified by suburban single family streets, very low density residential developments, and rural or semirural areas.	10 or fewer pedestrians/hour

Notes: ¹ For purposes of intersection lighting levels only.

² Pedestrian volumes during the average annual first hour of darkness (typically 18:00-19:00), representing the total number of pedestrians walking on both sides of the street plus those crossing the street at non-intersection locations in a typical block or 656 ft section. RP-8-00 clearly specifies that the pedestrian volume thresholds presented here are a local option and should not be construed as a fixed warrant.

Source: Reference 70, sections 2.1, 2.2, and 3.6