
Fundamentals of Signalized Intersections

Course No: C05-025

Credit: 5 PDH

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Introduction to the Study Guide

The Study Guide for the present course consists of Chapters 2-4 of Report No. FHWA-HRT-04-091, "Signalized Intersections: Informational Guide," written by Lee A. Rodegerdts, et al, August, 2004, and sponsored by the Federal Highway Administration under Contract No. DTFH61-98-C-00075, Task Order No. B98C75-009. These chapters have been excerpted and begin on the next page

The entire Report can be downloaded by clicking on this [link](#), but the present course is based solely on the material in Chapters 2-4.

2. ROAD USER NEEDS

The purpose of this chapter is to describe road user needs. The description is based on three assumptions:

- Practitioners want to 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.
- Practitioners need to fully understand and quantify intersection operations and safety performance in the pursuit of informed and balanced decisionmaking.

A discussion of user needs requires an understanding of human factors principles for all intersection users. This chapter begins with an overview of human factors research and is 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.

Documents marked with an asterisk in the reference list provide additional coverage of user needs and human factors and helpful background reading.

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 workplaces. The goal of human factors analysis in road transportation is to:

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

At signalized intersections, the application of human factors principles to the problems of safety and efficiency requires an approach that is both systems oriented and human-centered. A systems approach recognizes the interaction between the road user and road/roadway environment. This 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 decisionmakers—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 capabilities under a broad range of circumstances.
- Designing facilities that are accessible to and usable by all road users.
- Anticipating how road users may react to specific situations to ensure a predictable, timely, accurate and correct response, thus avoiding situations that violate road users' expectations.
- Designing and applying appropriate traffic control devices so they are conspicuous, legible, comprehensible, credible, and 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. Within each road user group, there are multiple user types. For example, motorists include passenger car and commercial truck drivers. Bicyclists include recreational and commuting bicyclists, as well as a wide range of ages and abilities. Pedestrians include all age groups (children, adults, elderly), some of whom have cognitive, mobility, or vision impairments. Each road user has unique abilities and characteristics, all of which need to be considered in the design of an intersection.

The basic function of signalized intersections is to sequence right-of-way between intersecting streams of 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. Intersections also serve as public right-of-way and include space for public utilities such as power and communication lines; water, sanitary sewer, and storm drainage pipes; and traffic signs and signal equipment.

Each road user has specific needs traversing an intersection. Motorists and cyclists must detect the intersection on 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.

Under ADA, all people, including those with disabilities, have the right to equal access to transportation.⁽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, and may have multiple impairments.

Road users are limited in the amount of information they can process. For vehicle drivers and bicyclists, the pace at which information is encountered increases with travel speed. The number of choices facing drivers and bicyclists at any one time should be minimized, and 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 brought forth 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.⁽⁸⁾

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 concepts are those of *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: if drivers are provided with all of the information they need, in a format they can readily read, interpret and apply, and in sufficient time to react appropriately, then the chances of driver error will be reduced, and relative safety will be

improved. 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 driver expectations that are correct and restructure those that are not. They must provide the information necessary to support rapid decisionmaking 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 that competition for driver attention, the presence of information irrelevant to driving-related tasks, as well as exceeding the information-processing limitations of drivers, may have a negative impact on relative 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 is suggesting 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. 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

In the past, roads were considered to be "safe" if they were designed, built, operated, and maintained in accordance with nominal standards. 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 don't just "happen," they are "caused," and that the roadway environment often 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.⁽⁹⁾

The concept of the "forgiving" roadway—one that minimizes the consequences of road user error by designing out or shielding hazards—has more recently given way to the "caring" roadway. The caring roadway combines all of the forgiving features of its predecessor (crash cushions, clear zones, etc.) with elements that respond to driver capabilities, limitations, expectations, and information needs. The caring roadway seeks to create an operating environment that is user-friendly and simplifies the information presented to the driver, a roadway that is conducive to rapid, error-free performance by the road user.

By attacking the environmental and situational elements that contribute to the occurrence of driver error, the caring roadway seeks to break the chain of causation between the erroneous decisions and/or actions, and their undesirable outcomes (e.g., crashes).

The caring 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, in sufficient time to react. Implicit in the caring 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 have the same 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 reaction times. The following section discusses human factor 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. Age plays a role in all of these factors. The following sections discuss each of these factors.

Human Vision

Road users 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.⁽¹⁰⁾ This means that information searches and the reading of long messages is carried out during a series of glances rather than with one long look. Complex or cluttered backgrounds, such as that shown in figures 1 and 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).



Figure 1. Traffic controls such as official signs need to be close to the road, distinctive from other information presentations, brief, and explicit. This photo provides an example of signs that are close to the road but may be confused with background information.

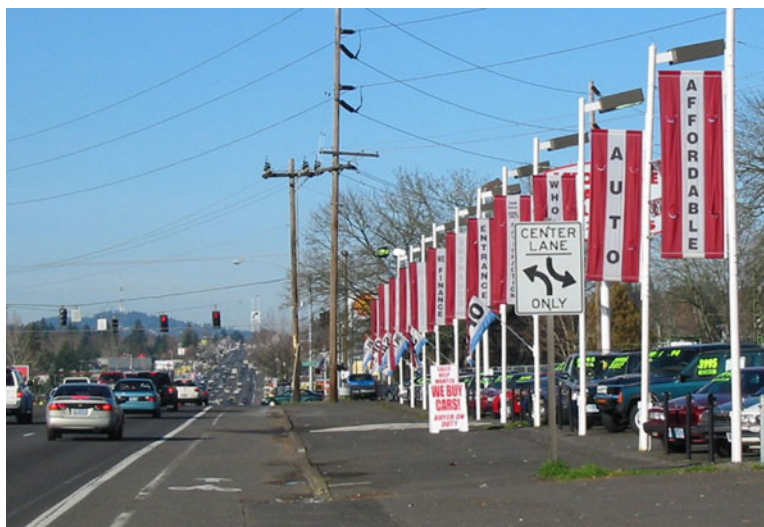


Figure 2. In terms of both official signs and advertising displays, too many displays may have the effect of causing drivers to “tune out,” and recall will be poor. This photo shows an example of sign clutter where the regulatory sign is difficult to isolate from the background advertising signs.

Information Processing

Road users perform best under moderate levels of demand. 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. 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.

Road users are adept at recognizing patterns—clues as to what is upcoming—and using those clues, along with expectations, 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, in time to perceive and react to it in an appropriate manner.

Memory

Humans have a limited short-term memory. Only a small percentage of what they see is actually remembered, including information presentations viewed while driving, cycling, or walking. Long-term memory is made up of experiences that have been ingrained through repetition. These are the source of our expectations. Expectations 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.

User Error

There is a common belief that the risk of user error is increased 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.

Information presentations must be conspicuous, legible, readable at a glance, and explicit as to their meaning. 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 in 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.⁽¹¹⁾ Cyclists 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 (violations by other road users, emergency vehicles traveling through red light).

- Inappropriate inputs (extraneous or conflicting signage).
- The shedding of important information when overloaded.
- Stress, frustration, inexperience, fatigue, intoxication.
- Imperfect decisionmaking.

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, cyclists, 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.⁽¹²⁾

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.⁽¹²⁾ 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 one ages, specific functions related to the driving task may deteriorate, such as vision, hearing, sensation, and cognitive and motor abilities. 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 driving and on foot).
- Following pavement markings.
- Responding to traffic signals.

Little research has been done on the performance and needs of young and inexperienced drivers at signalized intersections. Young drivers aged 16 to 24 have a higher risk (2.5 times) of being involved in a collision compared to other drivers. Young pedestrians (i.e., pedestrians under the age of 12) also have a higher risk of being in a collision. These users may:

- Have difficulty in 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 (i.e. conversations between passengers and adjusting the stereo).
- 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 225 million licensed vehicles in the United States.⁽¹³⁾ Traffic engineers have traditionally sought to design and operate intersections with the 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.

Road users—drivers, bicyclists, and pedestrians—are not homogeneous in their characteristics, and 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., teenaged drivers, older drivers, and aggressive drivers).

Most drivers traveling through signalized intersections will be operating passenger vehicles. These may be cars, but in ever-increasing numbers they are minivans, pickups and sports utility vehicles. More than 22,000 fatal collisions in the United States each year involve passenger vehicles.⁽¹⁴⁾ 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.⁽¹⁵⁾ 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 that should be considered.

Table 4 identifies general characteristics of vehicle types, and table 5 shows the frequency of fatalities and injuries by mode.

Table 4. Estimated number of registered vehicles by type, 2002.

Vehicle Type	Number of Registered Vehicles	Percent of Total
Passenger car (convertibles, sedans, station wagons)	133.6 million	59
Other 2-axle, 4-tire vehicles (pick-up trucks, vans, sport utility vehicles)	79.1 million	35
Motorcycles	4.3 million	2
Truck, single unit	5.9 million	3
Truck, combination	2.1 million	1
Bus	0.8 million	< 1
Total	225.8 million	

Source: Bureau of Transportation Statistics, 2002.⁽¹⁶⁾

Table 5. Fatalities and injuries by mode, 2001.

Mode	Fatalities	Percent of Total	Injuries	Percent of Total
Passenger car occupants (all types)	20,233	48	1,926,625	64
Truck occupants ¹	12,381	29	889,951	29
Motorcyclists	3,181	8	60,236	2
Bus occupants	34	< 1	15,427	1
Pedestrians	4,882	12	77,619	3
Bicyclists	728	2	45,277	1
Other	677	1	17,536	1
Total	42,116		3,032,672	

¹ Includes single-unit trucks, truck tractors, pickups, vans, truck-based station wagons, and utility vehicles.

Source: Bureau of Transportation Statistics, 2001⁽¹⁷⁾

Crash data from the Highway Safety and Information System (HSIS) database for the State of California were summarized to identify the proportion of crashes by ranges of Average Daily Traffic (ADT) for movements entering the intersection and the proportion of crashes by collision type. The HSIS data includes all reported crashes at signalized intersections for the period between 1994 and 1998. Table 6 presents a summary of total and injury/fatal crashes by volume, and table 7 presents the results and identifies the proportion of crashes by collision type for signalized intersection based on the California HSIS data.

Table 6. Total motor vehicle crashes and injury/fatal collisions at signalized intersections by total ADT entering the intersection.

ADT	Intersections (percent of total)	Total Crashes (percent of total)	Injury/Fatal Crashes (percent of total)
<20000	16	8	7
20,000-40,000	45	40	38
40,000-60,000	29	36	37
60,000-80,000	8	13	14
80,000 and more	2	3	4
TOTAL	100	100	100

Source: HSIS California database, 1994-1998⁽¹⁸⁾

As shown in table 6, the 20,000 to 40,000 ADT and 40,000 to 60,000 ADT ranges represent the greatest percentage of signalized intersections from the database and have the highest percentage of total crashes and injury/fatal crashes. The percentage of total and injury/fatal crashes that occurred in the 40,000-60,000 ADT range is similar; however, the proportion of intersections in this range is much smaller.

Table 7. Proportion of crashes by collision type at signalized intersections.⁽¹⁸⁾

Collision Type	Percent
Head on	3
Sideswipe	12
Rear end	42
Broadside	28
Fixed object	6
Overtaken	0
Pedestrian	3
Other	6
TOTAL	100

As shown in table 7, the most frequently occurring collision is a rear-end crash, which represents 42 percent of all reported intersection crashes in the database.

Vehicle Dimensions

Motor vehicle needs at a signalized intersection are governed by the dimensions of the design vehicle, which is the largest vehicle reasonably expected to use the intersection. Commonly, WB-15 (WB-50) vehicles, or truck/trailer combinations with a wheelbase of 15 m (50 ft), are the largest vehicles along many arterials. However, many signalized intersections are located on State highways where the design vehicle is an interstate vehicle such as a WB-20 (WB-67), or a truck/trailer combination with a wheelbase of 20 m (67 ft). Specific information on the dimensions for these and other design vehicles can be found in standard references.⁽³⁾

Design vehicles need to be carefully considered wherever they are expected to make a turning movement through the intersection. Affected elements include corner radii, channelization islands, median noses, and stop bar locations. In accommodating the design vehicle, however, tradeoffs for other users need to be acknowledged, such as the increase in pedestrian crossing distance or the accommodation of cyclists around channelization islands.

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. It is estimated that approximately 750 fatalities and 150,000 injuries occur on a yearly basis due to red light running. A study of HSIS data determined that red light runners cause 16 to 20 percent of all collisions at signalized intersections.⁽¹⁹⁾

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.

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 given in figure 3.



Figure 3. Enforcement cameras, as shown in the photo above, are used at signalized intersections to identify red light runners.

Driver Distraction

Despite the complexity of the driving task, it is not uncommon to see drivers engaging 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. One report estimated that 13 percent of all collisions occur due to driver distraction. Drivers involved in collisions at intersections were more likely to report that they “looked but didn’t see.” Drivers involved in intersection collisions as opposed to other driving situations reported that they were more likely to be distracted by:⁽²⁰⁾

- An outside person, object, or event.
- Another occupant in the vehicle.
- Vehicle and climate controls.
- Eating food.
- Using or dialing a cell phone.

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 cycling. Given the increases in traffic congestion over the past few decades, particularly in urban areas, the number of people that use bicycles to commute to work is on the rise.⁽²¹⁾

Bicyclists have unique needs at signalized intersections. Bicyclists are particularly vulnerable because they share the roadway with motorists and follow the same rules of the road, yet they do not possess nearly the same attributes in 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 for 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.⁽²¹⁾ To accomplish this, planning for bicycle use, whether existing or potential, should be integrated into the overall transportation planning process.

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. A 1994 report by FHWA defined the following general categories (A, B, and C) of bicycle user types:⁽²²⁾

- “**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

Bicyclists require at least 1.0 m (40 inches) of operating space, with an operating space of 1.2 m (4 ft) as the minimum width for bike lanes or other facilities designed for exclusive one-way or preferential use by bicyclists (see figure 4). For facilities where motor vehicle volumes, motor vehicle or bicyclist speed, and the mix of truck and bus traffic increase, such as most high-volume signalized intersections, a more comfortable operating space of 1.5 m (5 ft) or more is desirable.⁽²²⁾ In addition, because most bicyclists ride a distance of 0.8 to 1.0 m (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.⁽²²⁾ Where drain inlets are unavoidable, their drainage slots should not run parallel to the direction of travel, as these 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.

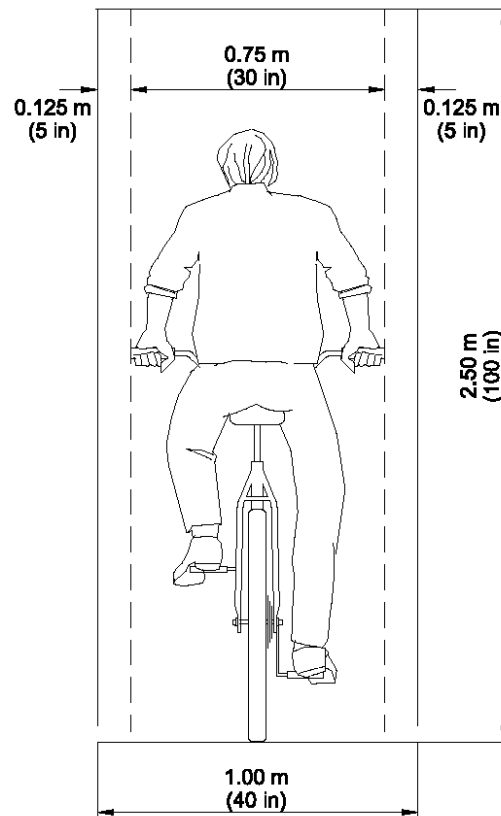


Figure 4. Typical dimensions of a bicyclist.

- Width—1.2 m (4 ft) design minimum for exclusive bicycle lanes; 1.5 m (5 ft) design minimum where motor vehicle traffic volumes, motor vehicle or bicyclist speed, and/or the mix of truck and bus traffic increase; bicycle lane width is the affected intersection feature.
- Length—1.8 m (5.9 ft), median island width at crosswalk is the affected intersection feature.
- Lateral clearance on each side—0.6 m (2.0 ft); 1.0 m (3.3 ft) to obstructions; shared bicycle-pedestrian path width is the affected intersection feature.

Sources: (22); (6), as adapted from (23)

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

- **Accessible and coherent.** The cycle 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 cycle network is not direct, logical, and easy to use, some cyclists will choose roads not planned for bicycle traffic.
- **Safe and secure.** Adequate visibility and curve radii should make it possible for cyclists to travel safely at a minimum of 25 km/h (15 mph). Parked cars, vegetation, barriers, etc. can result in poor or reduced visibility. Awareness of 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 cyclists 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.⁽²⁴⁾

Bicycle Safety

In 2001, the National Highway Traffic Safety Administration (NHTSA) reported that 728 bicyclists were killed and 45,000 injured in motor vehicle crashes.⁽²⁵⁾ 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.⁽²⁶⁾ 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 four common crash types, three of which occur at intersections:⁽²⁷⁾

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

Figure 5 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 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 cyclists 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 figure 5. As the size of the intersection increases, the difficulty for cyclists to weave to the left turn lane can be daunting for Category B and even some Category A cyclists.

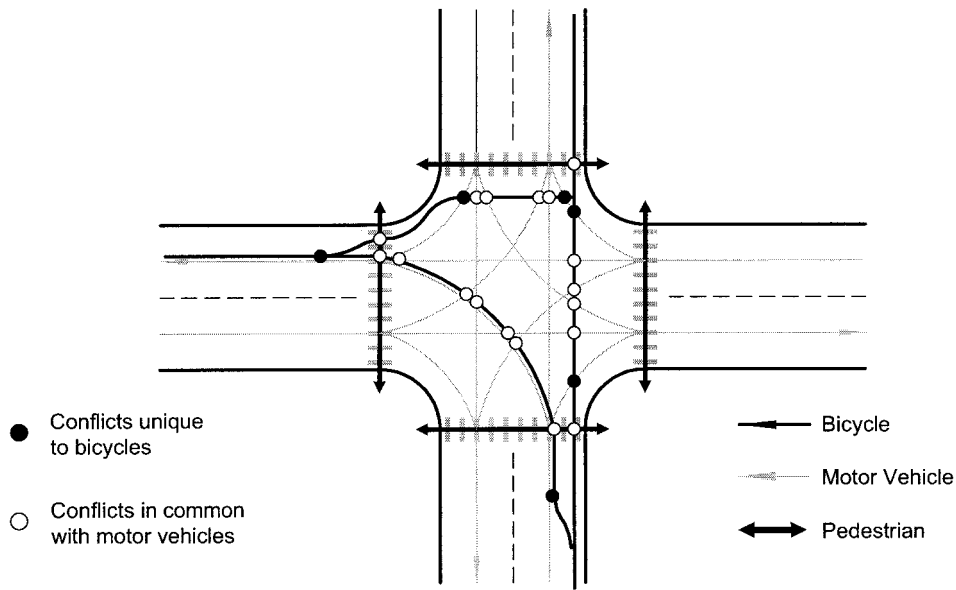


Figure 5. Bicyclist conflicts at signalized intersections.

Research confirms that the conflicts described above result in high risk for bicyclists at signalized intersections. Geary examined nearly 4,000 bicycle fatalities recorded on American roads during the period 1994-1998 with the use of the Fatality Analysis Reporting System database maintained by NHTSA.⁽²⁸⁾ The research indicated that intersections are far more involved in the injury-producing bicyclist crashes (73 percent) than in the fatal crashes (37 percent). Intersection-related fatalities are far more common on urban rather than rural roads, and during daylight instead of after dark. Recent trends suggest that adults are becoming more involved in collisions involving bicycles, while children are becoming less involved.

An analysis of police-reported collisions between bicyclists and motorists that occurred in Toronto, Canada, indicated that 17 percent of bicycle collisions occur at signalized intersections.⁽²⁹⁾ In just over half of these crashes, the cyclist was struck while crossing the intersection within the pedestrian crosswalk.

A Vancouver study found that the risk for collision while cycling is approximately three times higher than for driving a motor vehicle over the same distance.⁽³⁰⁾ The ratio varies between 2:1 and 6:1 in other British Columbia jurisdictions. Right-angle collisions were the most frequent collision type (28 percent of all collisions). Collisions that occur at signalized intersections accounted for 17 percent of all collisions.

2.2.4 Pedestrians

Walking is the oldest and most basic form of transportation. Nearly every trip includes a walking element. According to the *2001 Nationwide Personal Transportation Survey*, 8.6 percent of all daily trips occurred via the walk mode.⁽³¹⁾ 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. 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 figure 6. The design of intersection facilities should accommodate all types of pedestrians, because the user cannot be anticipated.



Figure 6. Examples of pedestrians of various abilities preparing to cross an intersection.

Pedestrian Dimensions

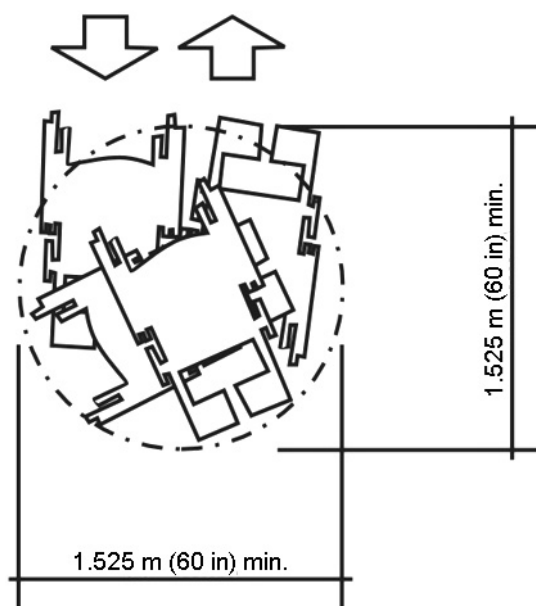
Research has shown that the ambulatory human body encompasses an ellipse of 45 by 60 cm (18 by 24 inches).⁽³²⁾ This dimension, however, does not account for a variety of scenarios, including pedestrians walking side by side; persons using canes, walkers, dog guides, or wheelchairs; persons with shopping carts or baby carriages, and so on. Table 8 shows dimensions for various types of pedestrians.

The Americans with Disabilities Act Accessibility Guidelines (ADAAG), specifies a 1.525-m (60-inch) square area to allow a wheelchair user to make a 180-degree turn (figure 7).⁽³³⁾ For parallel approaches, ADAAG specifies a minimum low-side reach of 0.23 m (9 inches) and a maximum high-side reach of 1.37 m (54 inches). For a forward approach, ADAAG specifies a minimum low-reach point of 0.38 m (15 inches) and a maximum high-reach point of 1.22 m (48 inches).

Table 8. Typical dimensions for a sample of types of pedestrians.

User and Characteristic	Dimension	Affected Intersection Features
Pedestrian (walking) Width	0.5 m (1.6 ft)	Sidewalk width, crosswalk width
Wheelchair Minimum width	0.75 m (2.5 ft)	Sidewalk width, crosswalk width, ramp landing areas
Operating width	0.90 m (3.0 ft)	
Person pushing stroller Length	1.70 m (5.6 ft)	Median island width at crosswalk
Skaters Typical operating width	1.8 m (6 ft)	Sidewalk width

Source: (6), as adapted from (23).



Source: (Reference 33, figure 3a)

Figure 7. Typical dimensions for a turning wheelchair.

Pedestrian Characteristics

Pedestrian walking speeds generally range between 0.8 to 1.8 m/s (2.5 to 6.0 ft/s).⁽³⁾ The MUTCD uses a walk speed of 1.2 m/s (4.0 ft/s) for determining crossing times.⁽¹⁾ However, FHWA pedestrian design guidance recommends a lower speed of 1.1 m/s (3.5 ft/s) 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.^(34,35) The *HCM 2000* indicates that if elderly persons constitute more than 20 percent of the total pedestrians, the average walking speed decreases to 0.9 m/s (3.0 ft/s).⁽²⁾



Figure 8. Crosswalks are used by a variety of users with different speed characteristics. Pedestrian walking speeds generally range between 0.8 to 1.8 m/s (2.5 to 6.0 ft/s).

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 (reference 7, chapter 18 of *HCM 2000*).⁽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

Figure 9 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.

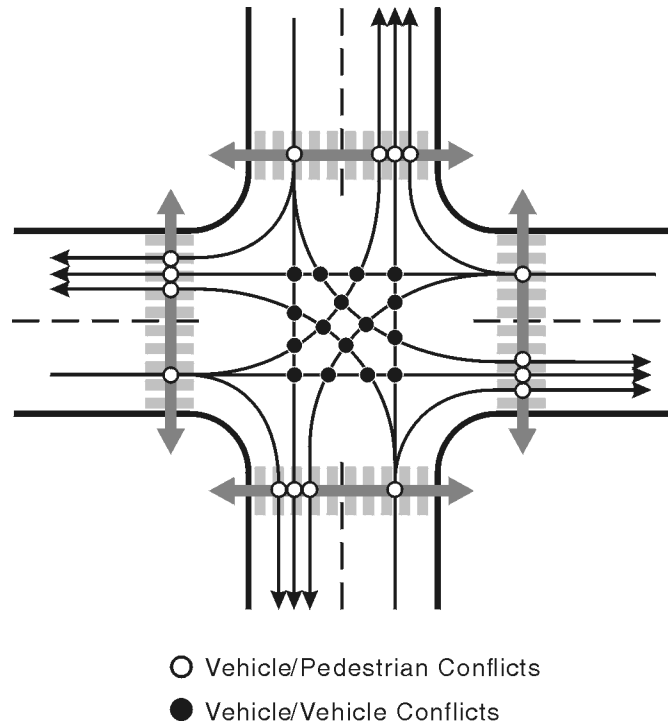


Figure 9. Pedestrian conflicts at signalized intersections.

In addition, 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 motorist's view of each other, thus putting the pedestrian at greater risk. This type of conflict may be present at signalized intersections in the following situations:

- *Double right-turn movements.* These may be in 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

The safety of pedestrians 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. Data from the Bureau of Transportation Statistics shows that in 2001, there were a total of 4,882 pedestrian fatalities involved in motor vehicle crashes; this represents 12 percent of all the 42,116 motorist collisions. More than 77,000 pedestrians were injured in motor vehicle collisions during this time.⁽¹⁷⁾

Of all crashes between single vehicles and pedestrians in 2001, 940 (22 percent) occurred at intersections (both signalized and unsignalized).⁽³⁶⁾ Speed plays a major role in motorist-pedestrian collisions, particularly fatalities; a pedestrian struck at 65 km/h (40 mph) has an 85-percent chance of being killed, at 48 km/h (30 mph) the probability of fatality is 45 percent, and at 30 km/h (20 mph) the probability of fatality drops to 5 percent.⁽³⁷⁾ Compounding the problem, motorists rarely stop to yield to a pedestrian when their speeds are greater than 70 km/h (45 mph); they are likely to stop when their speeds are less than 30 km/h (20 mph).⁽³⁸⁾

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.⁽³⁸⁾

The time required for a driver to detect a pedestrian, decelerate, and come to a complete stop is oftentimes underestimated, or worse yet, not even considered as part of the geometric design of an intersection. AASHTO's *A Policy on Geometric Design of Highways and Streets* recommends a brake reaction time of 2.5 s for determining stopping sight distance.⁽³⁾ Additional research has suggested that the value of 2.5 s has limitations and represents nearly ideal conditions with younger, alert drivers.⁽³⁹⁾ Research conducted by Hooper and McGee suggests that a perception-reaction time of 3.2 s is more reasonable.⁽⁴⁰⁾ Even then, 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.⁽³⁸⁾ 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."⁽³⁸⁾

Accessibility for pedestrians is also a key element. The ADA of 1990 mandates, among other things, that transportation facilities be accessible for all persons.⁽⁷⁾ This requires that new or altered facilities be designed to allow pedestrians of all abilities to identify the crossing location, access the pushbutton, know when to cross, and know where to cross. The Americans with Disabilities Act Accessibility Guidelines published by the U.S. Access Board in 1991 identify minimum design standards that must be applied to all new construction or alteration projects to adequately accommodate persons with disabilities.⁽³³⁾ The accommodation of all users needs to 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 achieve error-free road user performance 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 decisionmaking 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 illumination 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 table 4D-1 of the MUTCD.⁽¹⁾
- Phasing 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

GEOMETRIC DESIGN

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3. 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 the horizontal and vertical dimensions. Geometric design has a profound influence on 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 impedances, eliminating the need for lane changes and merge maneuvers, and minimizing the required distance to traverse an intersection all help improve the operational efficiency of an intersection.

The needs of all possible road users (see chapter 2) must be considered to achieve optimal safety and operational levels at an intersection. At times, design objectives may conflict between road user groups; 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.

This chapter addresses the following topics:

- Principles of channelization.
- Number of intersection approaches.
- Intersection angle.
- Horizontal and vertical alignment.
- Corner radius and curb ramp design
- Detectable warnings.
- Access control.
- Sight distance.
- Pedestrian facilities.
- Bicycle facilities.

3.1 CHANNELIZATION

A primary goal of intersection design is to limit or reduce the severity of potential road user conflicts. Basic principles of intersection channelization that can be applied to reduce conflicts are described below.⁽⁴¹⁾

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

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

Figure 10 shows how a raised median can be used to restrict undesirable turn movements within the influence of signalized intersections.



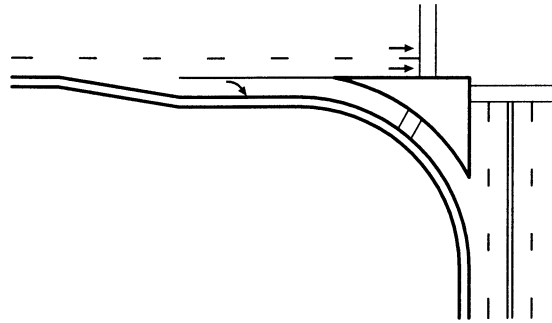
Figure 10. The photograph shows a raised median that restricts left-turn egress movements from a driveway located between two signalized intersections.

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 “unusual” geometry or traffic patterns such as highly skewed intersections, multileg 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 the safety and capacity at an intersection. Figure 11 shows how pavement markings can be applied to delineate travel paths.

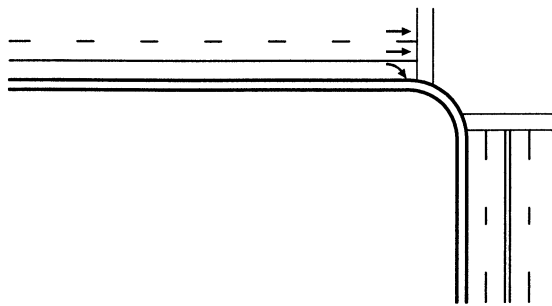


Figure 11. Pavement markings can be used to delineate travel lanes within wide intersections as shown in the photograph.

3. **Encourage safe speeds through design.** An 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, it may be desirable 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 curb radii. On low-speed roadways or in areas with pedestrians, promotion of lower turning speeds is appropriate. This can be accomplished with smaller turning radii, narrower lanes, and/or channelization features. These are illustrated in figure 12.



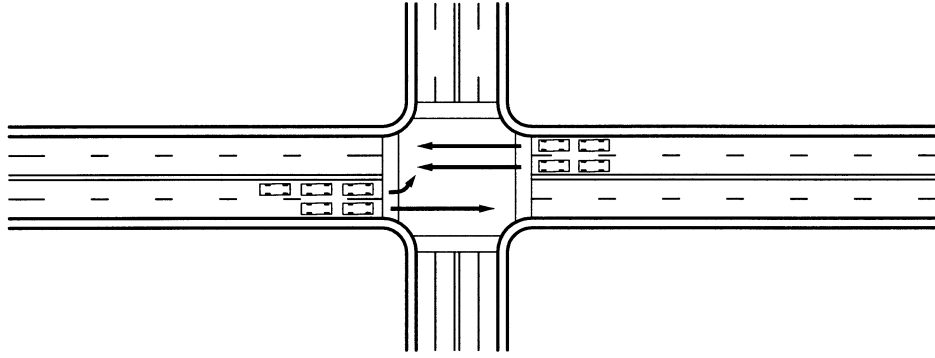
(a) Higher speed design



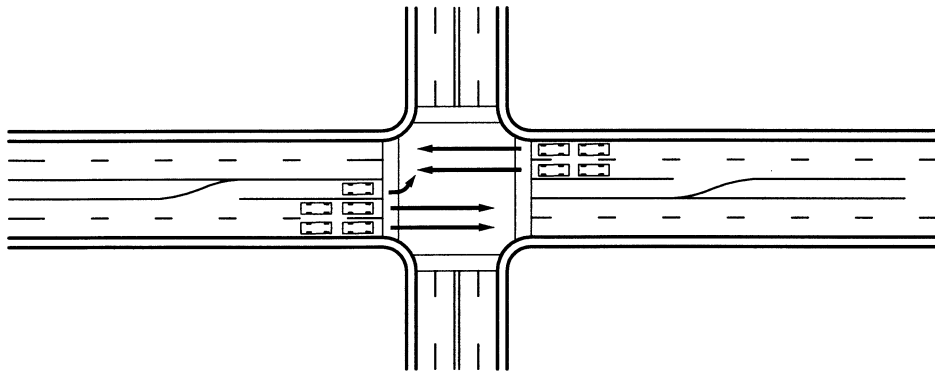
(b) Lower speed design

Figure 12. Various right-turn treatments may be used, depending on the speed environment.

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. Figure 13 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.

Figure 13. Providing a dedicated left-turn lane reduces potential collisions between left-turning and through vehicles, increasing the capacity of the approach for both left and through traffic.

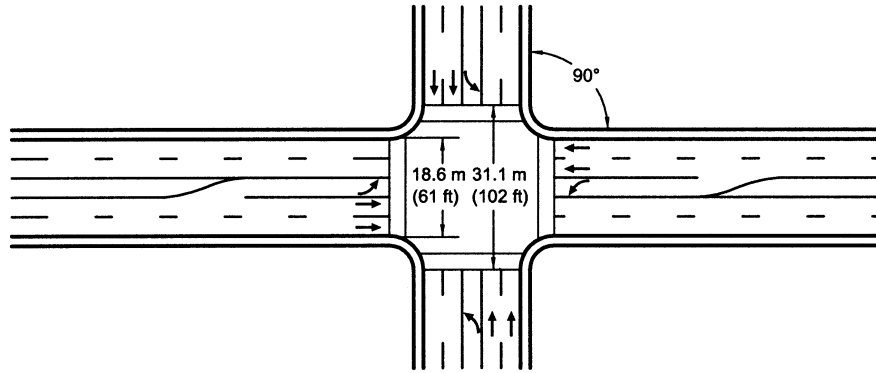
5. Facilitate the movement of high-priority traffic flows. Accommodating high-priority movements at intersections addresses both driver's expectations and intersection capacity. The highest volume movements at an intersection typically define the intersection's high-priority movements, although route designations and functional classification of intersecting roadways may also be considered. 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. Figure 14 shows an intersection where double left and right turn lanes are used to facilitate high-volume turning movements.



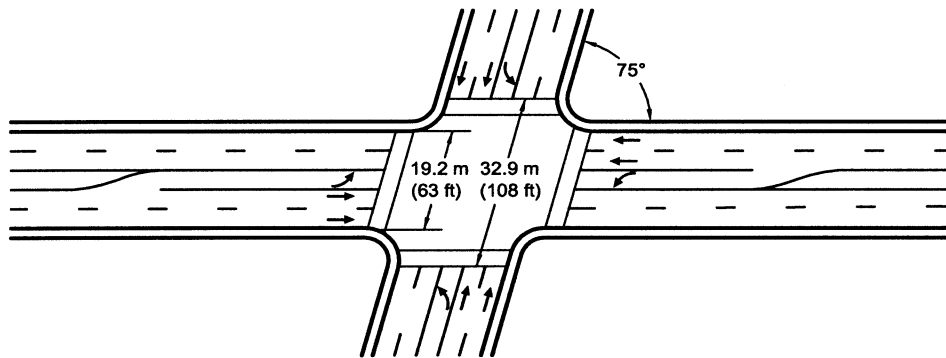
Photograph Credit and Copyright: www.portlandmaps.com, 2004

Figure 14. The photo shows how double left-turn and double right-turn lanes can be used to accommodate high-priority movements.

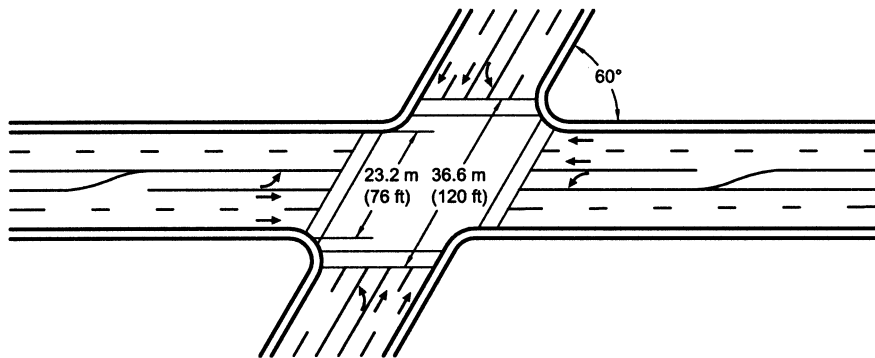
6. Design approaches to intersect at near right angles and merge at flat angles. Roadway alignments that cross as close to 90 degrees as practical can minimize the exposure of vehicles to potential conflicts and reduce the severity of a conflict. Skewed crossings produce awkward sight angles for drivers, which can be especially difficult for older drivers. Skewed crossings also result in additional distance for vehicles to traverse the intersections. This additional distance should be considered when developing the timing for a signal, as it may require the need for additional all-red clearance time. Figure 15 shows how a skewed intersection approach can increase the distance to clear the intersection for pedestrians and vehicles.



(a) Intersection skew at 90 degrees.



(b) Intersection skew at 75 degrees.



(c) Intersection skew at 60 degrees.

Figure 15. Intersection skew increases both the intersection width and pedestrian crossing distance.

7. Facilitate the desired scheme of traffic control. The design of a signalized intersection should attempt to maximize traffic safety and operations while providing operational flexibility. Lane arrangements, location of channelization islands, and medians should be established to facilitate pedestrian access and the placement of signs, signals, and markings. Consideration of these “downstream” issues as part of design can optimize the operation of an intersection. Providing exclusive left-turn bays that can accommodate left-turn movements can improve operations and safety while providing flexibility to accommodate varying traffic patterns. Positive offset left-turn lanes can improve sight distance for left-turning movements but may

prohibit U-turns if insufficient width is available. Reversible lanes may be appropriate for arterials that experience heavy directional peaks in traffic volumes during commuter periods.

8. 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 a turning maneuver. 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 will experience lower delay and fewer queues.

9. Provide safe refuge and wayfinding for bicyclists and pedestrians. Intersection design must consider the needs of roadway users other than motorists. Intersection channelization can provide refuge and/or reduce the exposure distance for pedestrians and bicyclists within an intersection without limiting vehicle movement. The use of raised medians, traffic islands, and other pedestrian-friendly treatments should be considered as part of the design process. Wayfinding may also be an issue, particularly at intersections with complicated configurations.

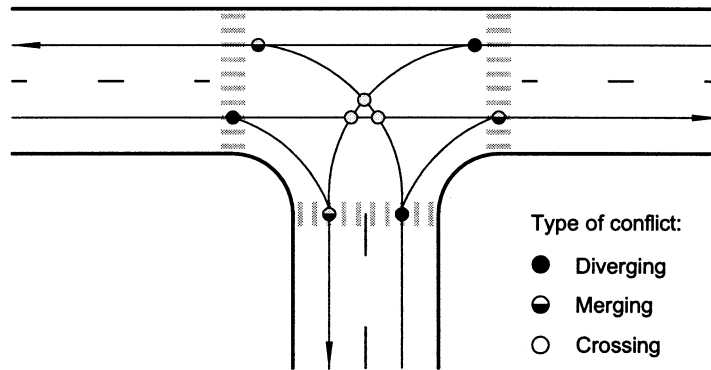
3.2 NUMBER OF INTERSECTION LEGS

While the geometry of various types of intersections may vary, the complexity of an intersection increases with an increasing number of approach legs to the intersections, as shown in figures 16 and 17. The latter shows the number and type of conflicts that occur at intersections with three and four legs, respectively. 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.

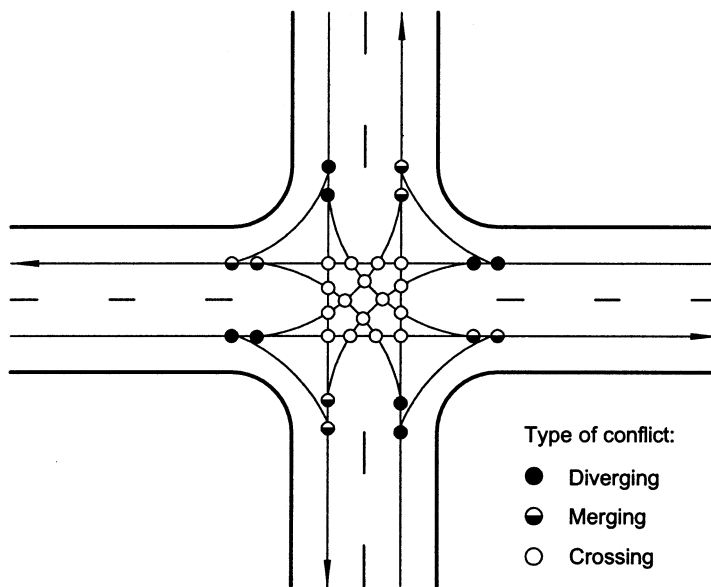


Photograph Credit and Copyright: www.portlandmaps.com, 2004

Figure 16. The photograph illustrates a multileg intersection.



(a) Three-leg intersection.



(b) Four-leg intersection.

Figure 17. Potential conflicts at intersections with three and four legs.

3.3 INTERSECTION ANGLE

The angle of intersection of two roadways can influence both the safety and operational characteristics of an intersection. Heavily skewed 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 in accommodating large vehicle turns. Additional pavement, channelization, and right-of-way may be required. The increase in pavement area poses potential drainage problems and gives smaller vehicles more opportunity to “wander” from the proper path.

- Vehicles crossing the intersection are more exposed to conflicts. This requires longer clearance intervals and increased lost time, which reduces the capacity of the intersection.
- Pedestrians and bicyclists are exposed to vehicular traffic longer. 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 result 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.⁽⁴²⁾ Conversely, drivers become more confused as they traverse curved or angled streets.

Skewed intersections are generally related to right-angle type crashes that can be associated with poor sight distance. AASHTO policy and many State design standards permit skewed intersections of up to 60 degrees.⁽³⁾ Gattis and Low conducted research to identify constraints on the angle of a left-skewed intersection as it is affected by the vehicle body's limiting a driver line-of-sight to the right.⁽⁴³⁾ 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.⁽¹²⁾

3.4 HORIZONTAL AND VERTICAL ALIGNMENT

The approach to a signalized intersection should promote awareness of an 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.

To meet the driver's or cyclist's expectations on approaches to an intersection, the following guidelines are suggested:

- Avoid approach grades to an intersection of greater than 6 percent. On higher design speed facilities (80 km/h (50 mph) and greater), a maximum grade of 3 percent should be considered.
- Avoid locating intersections along a horizontal curve of the intersecting road.
- Strive for an intersection platform (including sidewalks) with cross slope not exceeding 2 percent, as needed for accessibility.

3.5 CORNER RADIUS AND CURB RAMP DESIGN

Intersection corners that are designed appropriately accommodate all users. The selection of corner radius and curb ramp design should be guided by pedestrian crossing and design vehicle needs at the intersection. In general, it is recommended to provide a pedestrian crossing that is 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 more efficient operation of the signal. It also aids visually impaired pedestrians in their wayfinding task by eliminating changes in direction that may not be detectable.

Corner radii should also be designed to accommodate the turning path of a design vehicle to avoid encroachment on pedestrian facilities and opposing lanes of travel.

3.5.1 Corner Radius

The corner radii of an intersection should be designed to facilitate the turning and tracking requirements of the selected design vehicle. Other considerations when designing a corner radius include location of traffic control devices (signal poles, controller, signs, etc.), the need to provide channelizing islands, and available right-of-way. The corner radii should be compatible with other intersection features and the speed environment. For example, larger radii are more compatible with high-speed facilities with few pedestrians, whereas smaller radii are more compatible with low-speed facilities with many pedestrians.⁽⁴¹⁾

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. Often, a design vehicle is mandated by agency policy, regardless of vehicle mix. In certain instances, more than one design vehicle may be appropriate depending on traffic patterns.
- **Angle of intersection.** Large intersection skew angles make turning maneuvers more difficult, particularly for larger vehicles. This has the potential to increase the overall size of the intersection, making drainage difficult and increasing signal clearance intervals to clear the intersection.
- **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.** Multicentered curves or simple curves with tangent offsets can be used to better match the turn path of the design vehicle and reduce required right-of-way.

3.5.2 Curb Ramp Design

Curb ramps provide access for people who use wheelchairs and scooters. Curb ramps also aid people with strollers, luggage, bicycles, and other wheeled objects in negotiating the intersection. The basic components of a curb ramp, including ramp, landing, detectable warning, flare, and approach, are diagrammed in figure 18. The ADAAG require that curb ramps be provided wherever an accessible route crosses a curb, which includes all designated crosswalks at new and retrofitted signalized intersections.⁽³³⁾ 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 placed at the bottom of the ramp, which provides information on the boundary between the sidewalk and roadway.

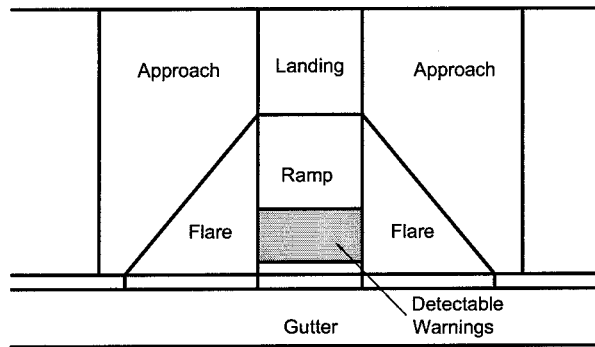


Figure 18. Curb ramp components.

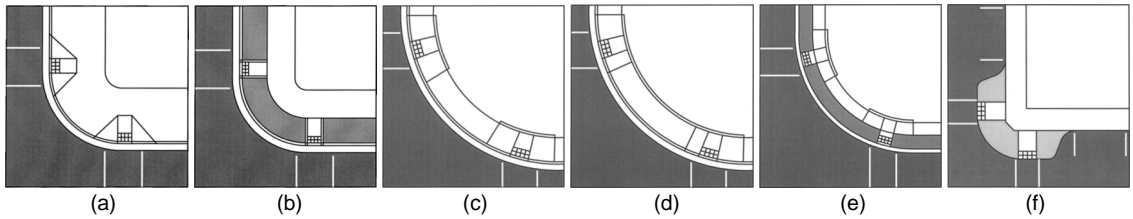
Table 9, adapted from FHWA's *Designing Sidewalks and Trails for Access, Part 2: Best Practices Design Guide*, provides a summary of recommended fundamental practices for curb ramp design, along with the rationale behind each practice.⁽³⁴⁾ A designer can apply these principles in designing intersections in a wide variety of circumstances.

Figures 19-21 provides 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.⁽³⁴⁾

Table 9. Summary of best practices for curb ramp design and associated rationale.

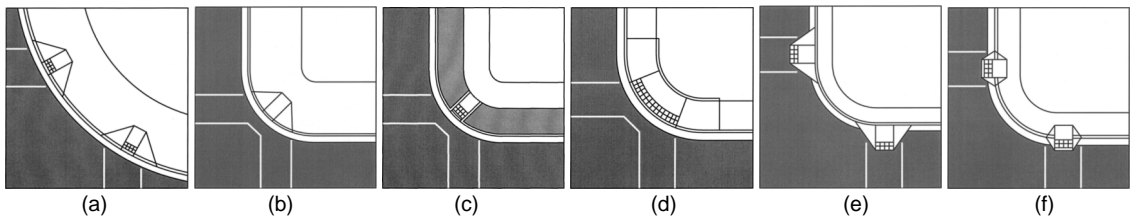
Best Practice	Rationale
Provide a level maneuvering area or landing at the top of the curb ramp.	Landings are critical to allow wheelchair users space to maneuver on or off the ramp. Furthermore, people who are continuing on the sidewalk will not have to negotiate a surface with a changing grade or cross slope.
Clearly identify the boundary between the bottom of the curb ramp and the street with a detectable warning.	Without a detectable warning, people with visual impairments may not be able to identify the boundary between the sidewalk and the street. (Note that detectable warnings are a requirement of ADA as of July 2001.)
Design ramp grades that are perpendicular to the curb.	Assistive devices for mobility are unusable if one side of the device is lower than the other or if the full base of support (e.g., all four wheels on a wheelchair) is not in contact with the surface. This commonly occurs when the bottom of a curb ramp is not perpendicular to the curb.
Place the curb ramp within the marked crosswalk area.	Pedestrians outside of the marked crosswalk are less likely to be seen by drivers because they are not in an expected location.
Avoid changes of grade that exceed 11 percent over a 610 mm (24 inch) interval.	Severe or sudden grade changes may not provide sufficient clearance for the frame of the wheelchair, causing the user to tip forward or backward.
Design the ramp so that it does not require turning or maneuvering on the ramp surface.	Maneuvering on a steep grade can be very hazardous for people with mobility impairments.
Provide a curb ramp grade that can be easily distinguished from surrounding terrain; otherwise, use detectable warnings.	Gradual slopes make it difficult for people with visual impairments to detect the presence of a curb ramp.
Design the ramp with a grade of 7.1 ±1.2 percent. Do not exceed 8.33 percent (1:12).	Shallow grades are difficult for people with vision impairments to detect, but steep grades are difficult for those using assistive devices for mobility.
Design the ramp and gutter with a cross slope of 2.0 percent.	Ramps should have minimal cross slope so users do not have to negotiate a steep grade and cross slope simultaneously.
Provide adequate drainage to prevent the accumulation of water or debris on or at the bottom of the ramp.	Water, ice, or debris accumulation will decrease the slip resistance of the curb ramp surface.
Provide transitions from ramps to gutter and streets that are flush and free of level changes.	Maneuvering over any vertical rise such as lips and defects can cause wheelchair users to propel forward when wheels hit this barrier.
Align the curb ramp with the crosswalk so there is a straight path of travel from the top of the ramp to the center of the roadway to the curb ramp on the other side.	Where curb ramps can be seen in advance, people using wheelchairs often build up momentum in the crosswalk in order to get up the curb ramp grade (i.e., they "take a run at it"). This alignment may be useful for people with vision impairments.
Provide clearly defined and easily identified edges or transitions on both sides of the ramp to contrast with the sidewalk.	Clearly defined edges assist users with vision impairments to identify the presence of the ramp when it is approached from the side.

Source: Adapted from reference 34, table 7-1.



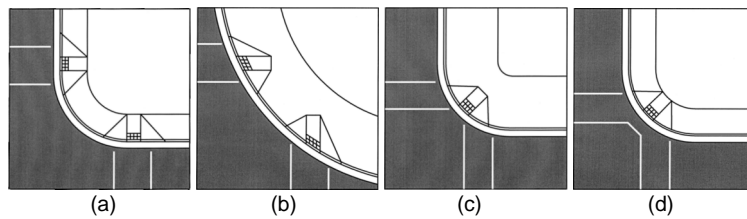
- a. Perpendicular curb ramps with flares and a level landing.
- b. Perpendicular curb ramps with returned curbs and a level landing.
- c. Two parallel curb ramps on a wide turning radius.
- d. Two parallel curb ramps with a lowered curb.
- e. Two combination curb ramps on a corner with a wide turning radius.
- f. A curb extension with two perpendicular curb ramps with returned curbs and level landings.

Figure 19. Examples of preferred designs.



- a. Perpendicular curb ramps, oriented perpendicular to the curb, on a corner with a wide turning radius.
- b. Diagonal curb ramp with flares and a level landing, in addition to at least 1.22 m (48 inch) of clear space.
- c. Diagonal curb ramp with returned curbs, a level landing, and sufficient clear space in the crosswalk.
- d. Single parallel curb ramp with at least 1.22 m (48 inch) clear space.
- e. Two built-up curb ramps.
- f. Partially built-up curb ramps.

Figure 20. Examples of acceptable curb ramp designs.



- a. Perpendicular curb ramps without a landing.
- b. On a corner with a wide turning radius, curb ramps are aligned parallel with the crosswalk.
- c. Diagonal curb ramp with no clear space or no level area at the bottom of the curb ramp.
- d. Diagonal curb ramps without a level landing.

Figure 21. Examples of inaccessible designs.

Source: Reproduced from reference 34, table 7-2

3.5.3 Detectable Warnings

The ADAAG require that a detectable warning surface be applied to the surface of the 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.⁽³³⁾ Detectable warnings consist of a surface 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, and provides 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 figure 22. The detectable warning surface begins at the curb line and extends into the ramp or pedestrian refuge area a distance of 610 mm (24 inches). For a median island, this creates a minimum clear space of 610 mm (24 inches) between the detectable warning surfaces for a minimum median island width of 1.8 m (6 ft) at the pedestrian crossing. This is a deviation from the requirements of the ADAAG (§4.29.5), which requires a surface width of 915 mm (36 inches). However, this deviation is necessary to enable visually impaired pedestrians to distinguish where the refuge begins and ends from the adjacent roadway where the minimum 1.8 m (6 ft) refuge width is provided.

Table 10 summarizes ADAAG requirements for detectable warning surfaces.



Photograph Credit: Lee Rodegerdts, 2003

Figure 22. This crosswalk design incorporates the use of detectable warning surfaces into the curb ramps to facilitate navigation by a visually impaired pedestrian.

Table 10. Requirements for detectable warning surfaces.

Legislation	<i>Americans with Disabilities Act Accessibility Guidelines</i> ⁽³³⁾	<i>Draft Guidelines on Accessible Public Rights-of-Way</i> ⁽⁴⁴⁾
Applicability	Required under existing regulations.	These guidelines are in the rulemaking process and are therefore not enforceable. They will be incorporated into the ADAAG; however, the recommendations listed below are subject to revision prior to the issuance of a final rule.
Type	Raised truncated domes.	Raised truncated domes aligned in a square grid pattern.
Dome Size	Nominal diameter: 23 mm (0.9 inches). Nominal height: 5 mm (0.2 inches).	Base diameter: 23 mm (0.9 inches) minimum, 36 mm (1.4 inches) maximum. Ratio of top diameter to base diameter: 50% minimum, 65% maximum. Height: 5 mm (0.2 inches).
Dome Spacing	Nominal center-to-center spacing: 60 mm (2.35 inches).	Center-to-center spacing: 41 mm (1.6 inches) minimum, 61 mm (2.4 inches) maximum. Base-to-base spacing: 16 mm (0.65 inches) minimum, measured between the most adjacent domes on square grid.
Contrast	Detectable warning surfaces must contrast visually with adjacent walking surfaces either light-on-dark, or dark-on-light. The material used to provide contrast must be an integral part of the walking surface.	Detectable warning surfaces must contrast visually with adjacent walking surfaces either light-on-dark, or dark-on-light.
Size	At curb ramps: The detectable warning must extend the full width and depth of the curb ramp. Within median islands, the boundary between the curbs must be defined by a continuous detectable warning 915 mm (36 inches) wide, beginning at the curb line.	At curb ramps, landings, or blended transitions connecting to a crosswalk: Detectable warning surfaces must extend 610 mm (24 inches) minimum in the direction of travel and the full width of the curb ramp, landing, or blended transition. The detectable warning surface must be located so that the edge nearest the curb line is 150 mm (6 inches) minimum and 205 mm (8 inches) maximum from the curb line. Within median islands, the detectable warning surface must begin at the curb line and extend into the pedestrian refuge a minimum of 610 mm (24 inches). Detectable warnings must be separated by a minimum length of walkway of 610 mm (24 inches) without detectable warnings.

The *Draft Guidelines on Accessible Public Rights-of-Way*, developed by the U.S. Access Board, issued a similar recommendation for use of a 610-mm (24-inch) width for detectable warning surfaces.⁽⁴⁴⁾ This is consistent with the existing ADAAG requirements for truncated dome detectable warning surfaces at transit platforms. The draft public right-of-way guidelines are based upon the recommendations of the Public Rights of Way Access Advisory Committee as published in the report *Building a True Community*.⁽⁴⁵⁾ For detectable warning surfaces, both the U.S. Access Board and FHWA are encouraging the use of the new (recommended) design pattern and application over the original ADAAG requirements.⁽³³⁾

3.6 SIGHT DISTANCE

A driver's 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.

3.6.1 Stopping Sight Distance

Stopping sight distance is the distance along a roadway 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. Stopping sight distance should be provided throughout the intersection and on each entering and exiting approach. Table 11 gives recommended stopping sight distances for design, as computed from the equations provided in the AASHTO policy.⁽³⁾

Table 11. 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, 3.4 m/s² (11.2 ft/s²) driver deceleration
Source: Reference 3, exhibit 3-1.

Stopping sight distance should be measured using an assumed height of driver's eye of 1,080 mm (3.5 ft) and an assumed height of object of 600 mm (2.0 ft).⁽³⁾

3.6.2 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 is applicable for 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. Table 12 gives recommended values for decision sight distance, as computed from equations in the AASHTO policy.⁽³⁾

Table 12. Design values for decision sight distance for selected avoidance maneuvers.

Speed (km/h)	Metric (m)					Speed (mph)	U.S. Customary (ft)				
	A	B	C	D	E		A	B	C	D	E
50	70	155	145	170	195	30	220	490	450	535	620
60	95	195	170	205	235	35	275	590	525	625	720
70	115	235	200	235	275	40	330	690	600	715	825
80	140	280	230	270	315	45	395	800	675	800	930
90	170	325	270	315	360	50	465	910	750	890	1030
100	200	370	315	355	400	55	535	1030	865	980	1135
110	235	420	330	380	430	60	610	1150	990	1125	1280
120	265	470	360	415	470	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: Reference 3, exhibit 3-3.

3.6.3 Intersection Sight Distance

Intersection sight distance is the distance required for a driver without the right of way to perceive and react to the presence of conflicting vehicles and pedestrians.

Intersection sight distance is traditionally measured through the determination of a sight triangle. This triangle is bounded 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 1,080 mm (3.5 ft) and an assumed height of object of 1,080 mm (3.5 ft).⁽³⁾ The area within the triangle is referred to as the clear zone and should remain free from obstacles.

The reader is encouraged to refer to the AASHTO policy, pp. 654-680, for a complete discussion of intersection sight distance requirements.⁽³⁾ Intersection sight distance at signalized intersections is generally simpler than for 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 (Case F, reference 3).
- Right turns on red should satisfy the case for a stop-controlled right turn from the minor road (Case B2, reference 3).

For signalized intersections where two-way flashing operation is planned (i.e., flashing yellow on the major street and flashing red on the minor street), departure sight triangles for Case B should be provided for the minor-street approaches.⁽³⁾

3.7 PEDESTRIAN FACILITIES

Pedestrian facilities should be provided at all intersections in urban and suburban areas. In general, design of the pedestrian facilities of an intersection with the most challenged users in mind—pedestrians with mobility or visual impairments—should be done. The resulting design will serve all pedestrians well. In addition, the ADA requires that new and altered facilities constructed

by, on behalf of, or for the use of State and local government entities be designed and constructed to be readily accessible to and usable by individuals with disabilities.⁽³³⁾ Therefore, it is not only good practice to design for all pedestrian types, but it is also a legal requirement.

Pedestrians are faced with a number of disincentives to walking, including centers and services located far apart, physical barriers and interruptions along pedestrian routes, a perception that routes are unsafe due to motor vehicle conflicts and crime, and routes that are esthetically unpleasing.⁽⁴⁶⁾

Key elements that affect a pedestrian facility that practitioners should incorporate into their design are listed below:⁽⁴⁷⁾

- Keep corners free of obstructions to provide enough room for pedestrians waiting to cross.
- Maintain adequate lines of sight between drivers and pedestrians on the intersection corner and in the crosswalk.
- Ensure curb ramps, transit stops (where applicable), pushbuttons, etc. are easily accessible and meet ADAAG design standards.
- Clearly indicate the actions pedestrians are expected to take at crossing locations.
- Design corner radii to ensure vehicles do not drive over the pedestrian area yet are able to maintain appropriate turning speeds.
- Ensure crosswalks clearly indicate where crossings should occur and are in desirable locations.
- Provide appropriate intervals for crossings and minimize wait time.
- Limit exposure to conflicting traffic, and provide refuges where necessary.
- Ensure the crosswalk is a direct continuation of the pedestrian's travel path.
- Ensure the crossing is free of barriers, obstacles, and hazards.

3.8 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 cyclists 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.
- Left turn bike lanes.
- Median refuges with a width to accommodate a bicycle: 2.0 m (6 ft) = poor; 2.5 m (8 ft) = satisfactory; 3.0 m (10 ft) = good.^(21, p. 52)
- Separate facilities if no safe routes can be provided through the intersection itself.

The interaction between motor vehicles and bicyclists at interchanges with merge and diverge areas is especially complex, and some signalized intersections also have merge and diverge areas due to free right turns or diverted movements (see chapter 10). 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.”^(21, p. 62)

CHAPTER 4

TRAFFIC DESIGN AND ILLUMINATION

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4. TRAFFIC DESIGN AND ILLUMINATION

This chapter deals with the traffic signal hardware and software—the infrastructure that controls the assignment of vehicular and pedestrian right-of-way 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 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.

4.1 TRAFFIC SIGNAL CONTROL TYPE

Traffic signals operate in either pre-timed or actuated mode. Pre-timed signals operate with fixed cycle lengths and green splits. Actuated signals vary the amount of green time allocated to each phase based on traffic demand. Either type may be used in isolated (independent) or coordinated operation. Most pre-timed controls feature multiple timing plans, with different cycle, split, and offset values for different periods of the day.

Actuated control does not rely on a fixed cycle length unless the intersection is in a coordinated system or under adaptive control. 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).

4.2 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 most intersections in the United States makes use of a standard National Electrical Manufacturers Association (NEMA) ring-and-barrier structure, shown in figure 23. This structure organizes phases to prohibit conflicting movements (e.g., eastbound and southbound through movements) from timing concurrently while allowing nonconflicting 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.

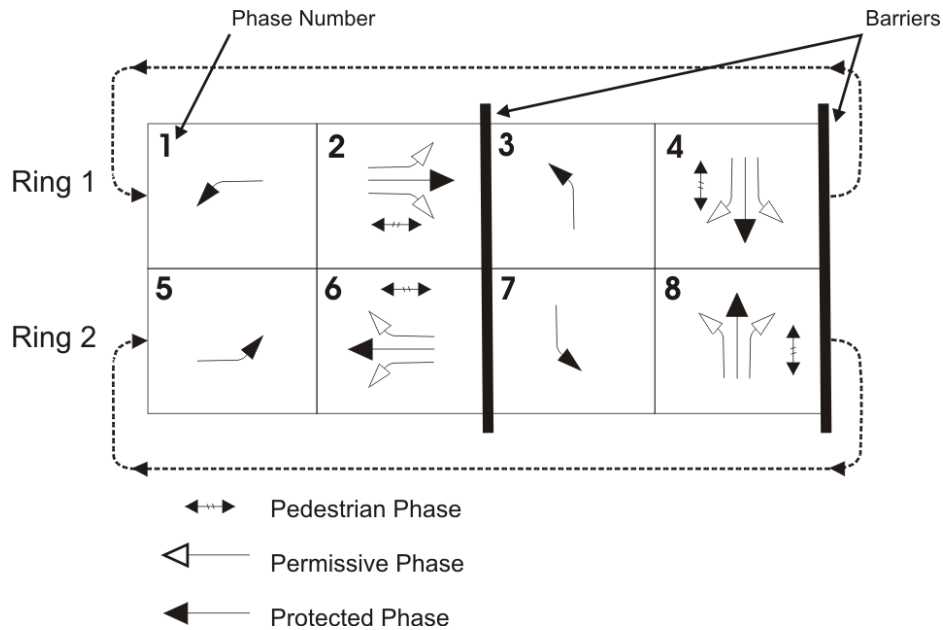


Figure 23. Standard NEMA ring-and-barrier structure.

Depending on the complexity of the intersection, 2 to 8 phases are typically used, although some controllers can provide up to 40 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 or pedestrians and provides no special protected interval for left turns. As a general rule, the number of phases should be kept to a minimum because each additional phase in the signal cycle reduces the time available to other phases.

Provision of a separate left-turn lane may alleviate the problems somewhat by providing storage space where vehicles can await an adequate gap without blocking other traffic movements at the intersection. In most cases, the development of a signal phasing plan should involve an analytical 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.

Pedestrian movements must be considered during the development of a phasing plan. 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.

4.2.1 “Permissive-Only” Left-Turn Phasing

“Permissive-only” (also known as “permitted-only”) phasing allows two opposing approaches to time concurrently, with left turns allowed after yielding to conflicting traffic and pedestrians. One possible implementation of this phasing pattern is illustrated in figure 24. 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 figure 24 could be assigned as phase 2 and phase 6, respectively.

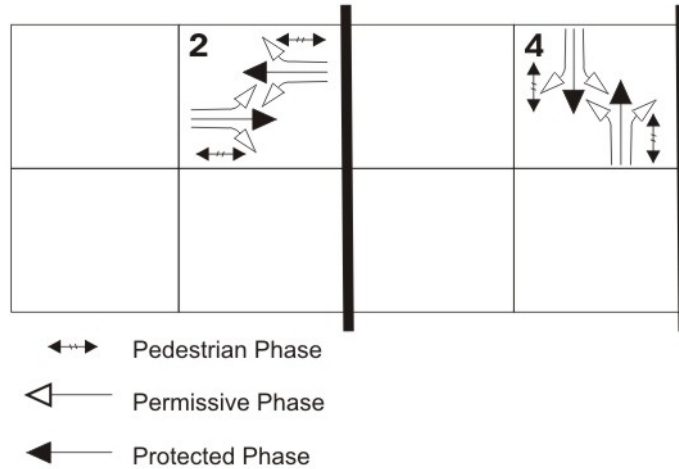
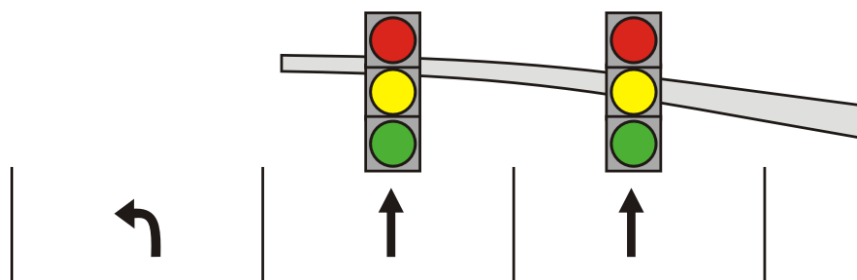


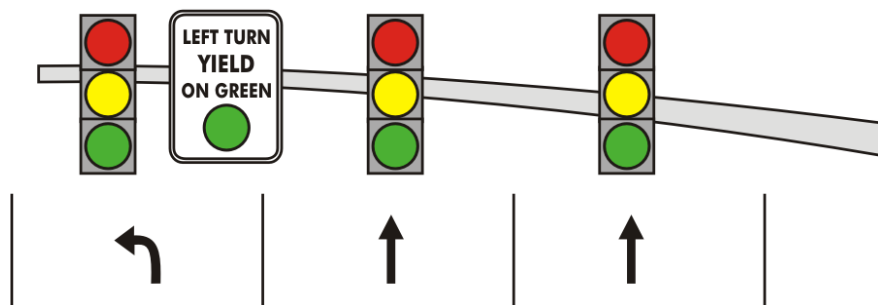
Figure 24. Typical phasing diagram for “permissive-only” left-turn phasing.

For most high-volume intersections, “permissive-only” left-turn phasing is generally not practical for major street movements given the high volume of the intersections. Minor side street movements, however, may function acceptably using “permissive-only” left-turn phasing, provided that traffic volumes are low enough to operate adequately and safely without additional left-turn protection.

“Permissive-only” displays are signified by a green ball indication. In this case, no regulatory sign is required, but the MUTCD (sections 2B.45 and 4D.06) allows the option of using the R10-12 regulatory sign (“LEFT TURN YIELD ON GREEN (symbolic green ball)”).⁽¹⁾ 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. Common signal head arrangements that implement “permissive only” phasing are shown in figure 25; 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 and accompanying sign over the left turn lane.

Figure 25. Possible signal head arrangements for “permissive-only” left-turn phasing.

4.2.2 “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. This phasing pattern is illustrated in figure 26. Typical signal head and associated signing arrangements that implement “protected-only” phasing are shown in figure 27; refer to the MUTCD for other configurations. Chapter 12 of this document provides guidance on determining the need for protected left turns.

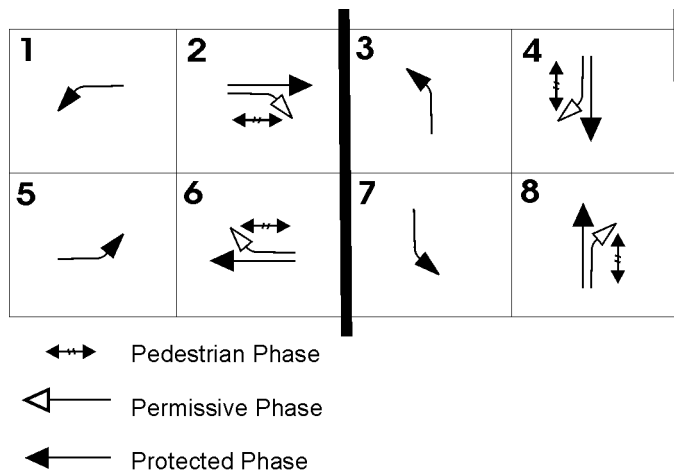
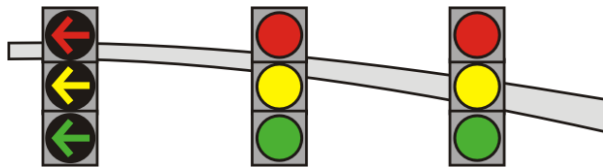
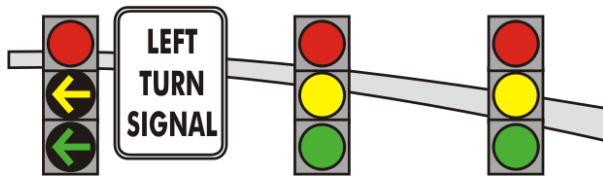


Figure 26. Typical phasing diagram for “protected-only” left-turn phasing.



(a) Protected left-turn phasing using a three-section signal head with red, yellow, and green arrows.



(b) Protected left-turn phasing using a three-section signal head with red ball, yellow arrow, and green arrow and an accompanying sign.

Figure 27. Possible signal head arrangements for “protected-only” left-turn phasing.

4.2.3 Protected-Permissive Left-Turn Phasing

A combination of protected and permissive left-turn phasing is referred to as protected-permissive left-turn (PPLT) operation. This phasing pattern is illustrated in figure 28. A typical signal head and associated signing arrangement that implements protected-permissive phasing is shown in figure 29; refer to the MUTCD for other configurations.

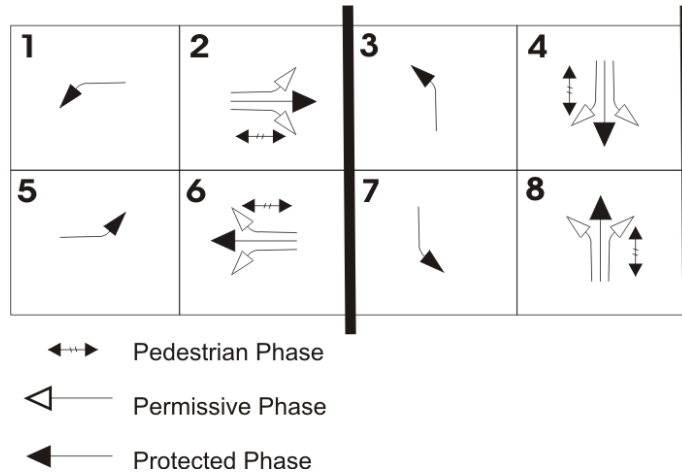
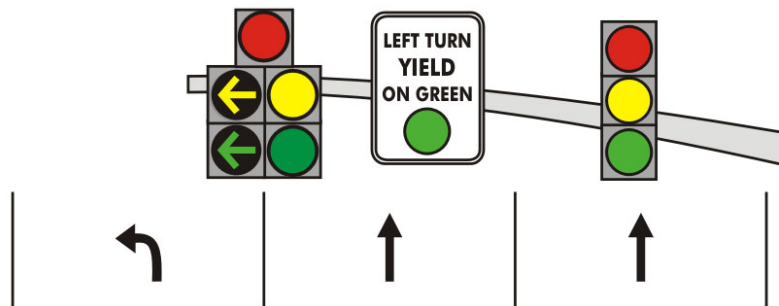
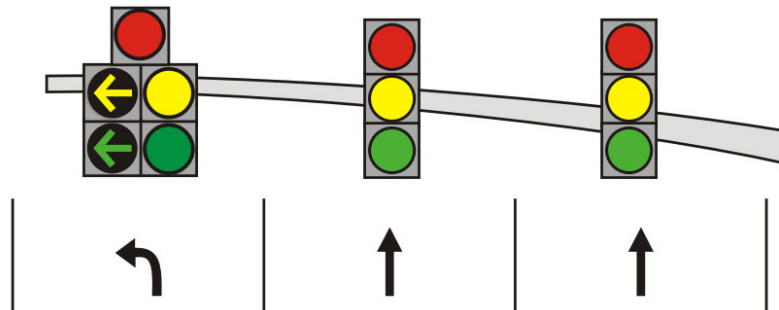


Figure 28. Typical phasing diagram for protected-permissive left-turn phasing.



(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 sign.



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

Figure 29. Possible signal head and signing arrangement for protected-permissive left-turn phasing.

Observed improvements in signal progression and efficiency combined with driver acceptance have led to expanded usage of PPLT over the years. PPLT signals offer numerous advantages when compared to “protected-only” operation. These advantages are associated with

both protected-permissive and lead-lag operation. They include the following (adapted with additions by the authors).⁽⁴⁸⁾

- 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.

Some disadvantages include the following:

- The permissive phase increases the potential for vehicle-vehicle and vehicle-pedestrian conflicts.
- There is a limited ability to use lead-lag phase sequences unless special signal head treatments are used (see below).

The controller phasing for protected-permissive mode is the most complicated phasing because of the safety implications created by the potential of what is known as the “yellow trap.” In a permissive-mode operation, the left-turning driver must obey the green display for the adjacent through movement, which also gives permission for the permissive left turn. When the yellow display for the adjacent through movement appears, the left-turning driver ordinarily expects the opposing through display to be yellow as well. The driver may now mistakenly believe that the left turn can be completed on the yellow display or immediately thereafter when the opposing through display will be red.

For ordinary lead-lead operation where both protected left-turn phases precede the permissive phases, this is not a concern, 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 may be yellow or may remain green. 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. This yellow trap is illustrated in figure 30.

Drivers who encounter this trap are those that attempt to make a permissive left-turn after a protected leading left-turn phase. Typically they 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 left-turn 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 cleared at the same time that the adjacent through movement is being terminated. Therefore, they may complete their turn believing that opposing vehicles are slowing to a stop when in fact the opposing vehicles are proceeding into the intersection with a green ball signal indication.

There are two ways to eliminate the yellow trap. First, the phase sequence at the intersection can be restricted to simultaneous leading (lead-lead) or lagging (lag-lag) left-turn phasing. Second, the signal display can be altered to allow the left-turn signal head to display a permissive left turn independently of the adjacent through movements, which allows the through movements to terminate but allow a permissive left turn to continue during the opposite approach’s lagging protected left-turn phase. Some agencies have experimented with signal displays (e.g., “Dallas Display,” flashing circular red, flashing red arrow, flashing circular yellow, and flashing yellow arrow) that allow this type of operation. Of these, the “Dallas Display” optically restricts the visibility of the permissive movement using louvers; it is fully compliant with the MUTCD and is shown in figure 31.

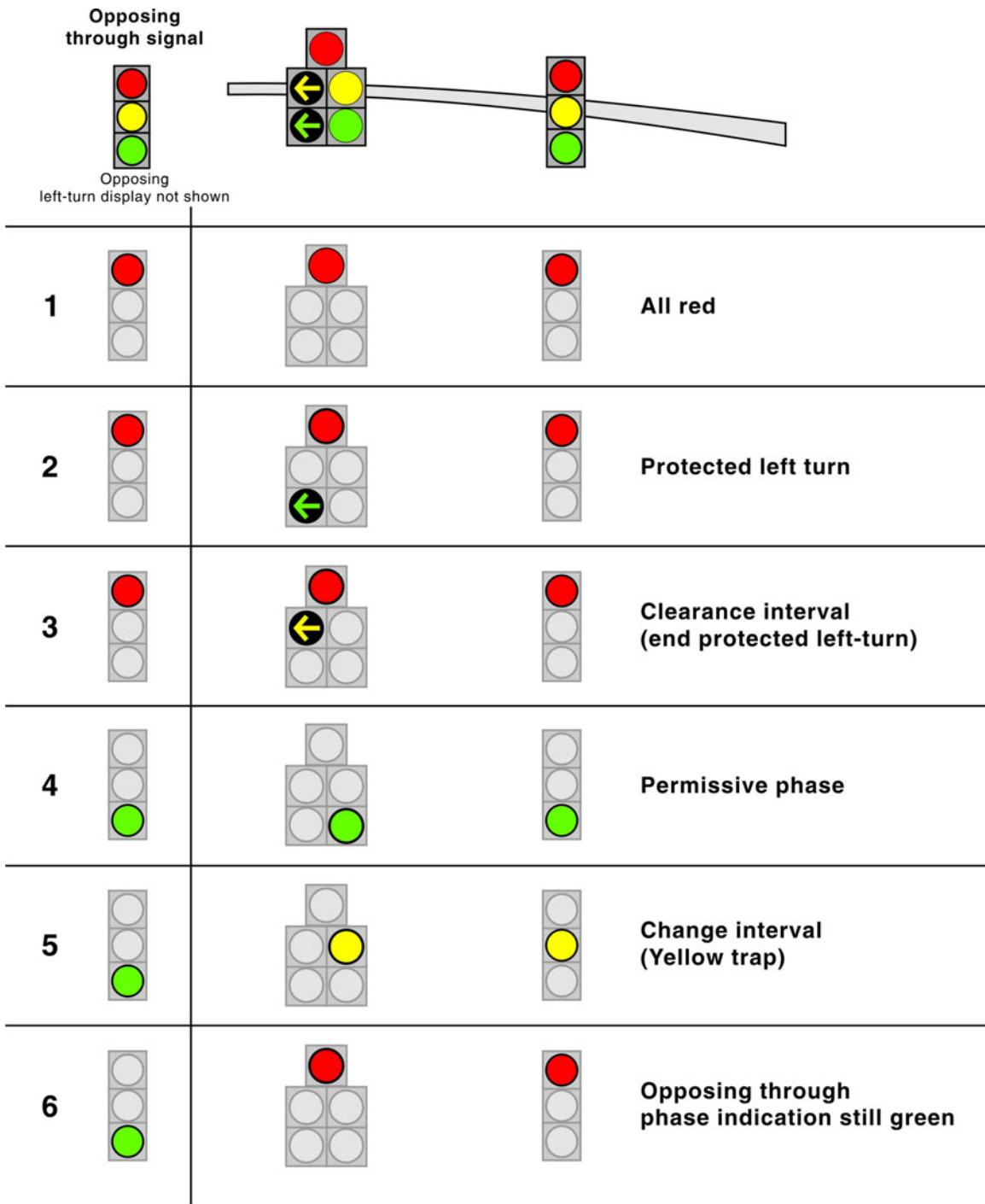


Figure 30. Illustration of the yellow trap.⁽³⁾

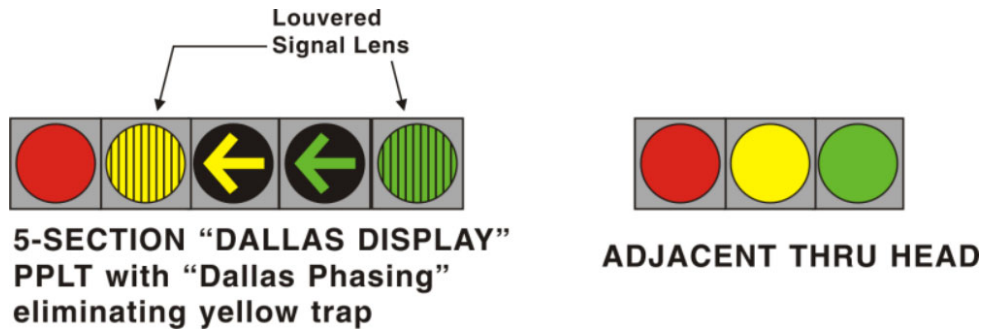


Figure 31. The protected-permissive left-turn display known as "Dallas display" uses louvers to restrict visibility of the left-turn display to adjacent lanes.⁽⁴⁹⁾

A national NCHRP study, has examined the operational advantages and safety aspects of various PPLT control devices and signal arrangements. The study determined that a flashing yellow arrow PPLT display was consistently found to be equal or superior to existing PPLT displays both in a laboratory environment and in cities where the display was experimentally implemented in the field.⁽⁴⁹⁾ The flashing yellow arrow display for PPLT is still considered experimental by the MUTCD and is undergoing further field testing.

4.2.4 Split Phasing

Split phasing consists of having two opposing approaches time consecutively rather than concurrently (i.e., all movements originating from the west followed by all movements from the east). Split phase can be implemented in a variety of ways depending on signal controller capabilities and how pedestrian movements are treated. Three basic variations, shown in figure 32, are described as follows:

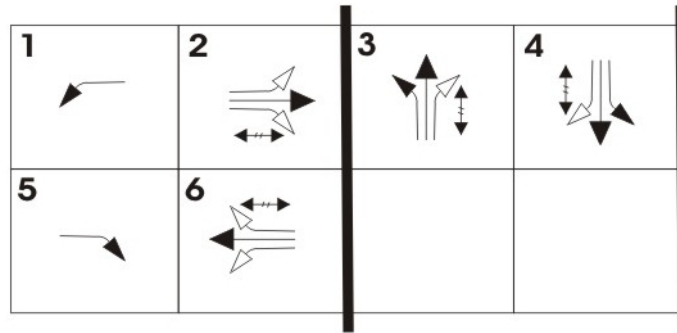
- **Method A: Consecutive pedestrian phases using one ring.** This method associates each pedestrian phase with its adjacent vehicle phase. This places pedestrians at potential conflict with right-turning traffic only. However, this may result in potentially consecutive pedestrian phases if pedestrian calls are present on both phases. For large intersections, the minimum time needed to serve these consecutive movements may result in excessively long cycle lengths. Implementation uses two consecutive phases in the same ring (e.g., phases 3 and 4), with pedestrian phases assigned to each.
- **Method B: Consecutive pedestrian phases using "exclusive" settings in controller.** This method is functionally identical to method A. Implementation differs from method A in that a setting in the controller is needed to force the phases to time in an "exclusive" mode (e.g., the phase must not time with any other phases).
- **Method C: Concurrent pedestrian phases using two rings.** This method, used by some agencies in certain situations, associates pedestrian movements with a single phase in one ring that, when actuated, operates concurrently with two consecutively timing vehicle phases in the second ring. Details of implementation of this method can be found in Wainwright.⁽⁵⁰⁾ This method can provide a considerably more efficient operation of the intersection, particularly where pedestrian crossing demands are large enough to warrant pedestrian signals but are relatively infrequent (not every cycle) during most or all of the day. In most cycles, no pedestrian actuation occurs, so:
 - The split vehicular phases operate without any pedestrian timing considerations.

- The sequential vehicular phase green times are directly related to their respective vehicular demands.
- The green left arrow signal indication is displayed to each of the sequential vehicle phases to encourage efficient nonyielding movement.

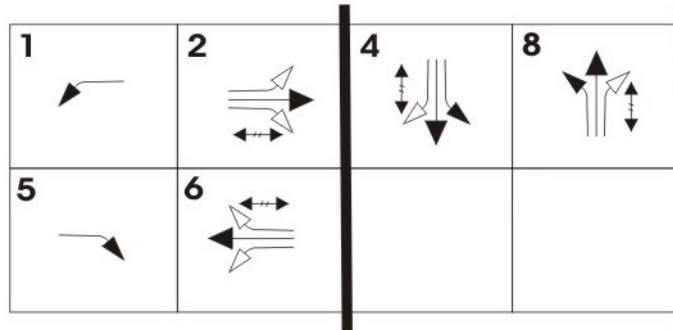
Method C is advantageous under some conditions, but should not be applied indiscriminately because it does have some potential liabilities as compared to the other two methods. Firstly, during the cycles when the pedestrian phase is actuated, left-turning vehicles can sometimes be placed in an awkward situation of not being able to clear the intersection when the vehicle phase terminates because conflicting pedestrians have not yet finished crossing. Secondly, pedestrians could face both left-turning and right-turning conflicting vehicles. Thirdly, if for some reason the timing parameters for the two crosswalks are different, then this method might be disadvantageous because placing both crosswalks on a single phase requires identical timing parameters for both crosswalks.

Split phasing is used infrequently at signalized intersections because a more efficient conventional phasing plan can usually be found. The following conditions could indicate that split phasing might be an appropriate design choice:

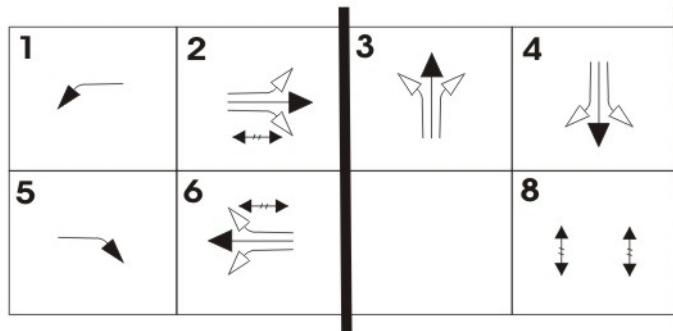
- There is a need to accommodate multiple turn lanes on an approach, but sufficient width is not available to provide separate lanes. Therefore, a shared through/left lane is required. An operational analysis should be performed to ensure this option is superior compared to a single turn lane option under various phasing scenarios.
- 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 to be more efficient than conventional phasing.
- 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.
- The angle of the intersection is such that the paths of opposing left turns would not be forgiving of errant behavior by turning motorists.
- 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.
- 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.
- 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.



(a) Method A: Consecutive pedestrian phases using one ring.



(b) Method B: Consecutive pedestrian phases using "exclusive" settings in controller.
 Note: Separate "exclusive" setting must be used for phases 4 and 8; otherwise, operation results in simultaneous display of phases 4 and 8.



- ↔ Pedestrian Phase
- ◁ Permissive Phase
- ◄ Protected Phase

(c) Method C: Concurrent pedestrian phases using two rings.

Figure 32. Typical phasing diagrams for split phasing.

No standard method is provided in the MUTCD for indicating split phasing at an intersection, and the methods vary considerably depending on what type of phasing sequence has been used. A common way to implement method A or B described above involves using a four-section head displaying both a green ball and a green left-turn arrow simultaneously, as shown in figure 33. This method does not require the use of additional signs. Note that additional measures are needed with method C, as the protected left-turn arrow conflicts with the concurrent pedestrian phase, as follows:⁽⁵⁰⁾

- A special logic package can be used to suppress the green arrow display whenever the pedestrian phase is being served.
- A static sign indicating “LEFT TURN YIELD TO PEDS ON GREEN (symbolic green ball)” can be located next to the leftmost signal head for emphasis.
- A blankout sign indicating “LEFT TURN YIELD TO PEDS” can be activated when the conflicting vehicular and pedestrian phases are running concurrently.

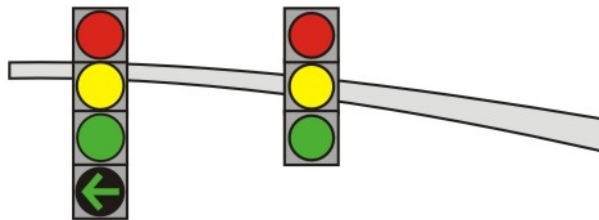


Figure 33. Common signal head arrangement for split phasing.

4.2.5 Prohibited Left-Turn Phasing

An alternative to providing a left-turn phase is to prohibit left-turn movements at the subject intersection. Under this scenario, left-turning drivers would be required to divert to another facility or turn in advance or beyond the intersection via a geometric treatment such as a jughandle or 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. A variety of treatments that redirect left turns are discussed in chapter 10.

4.2.6 Right-Turn Phasing

Right-turn phasing may be controlled in a permissive or protected manner with different configurations depending on the presence of pedestrians and lane configuration at the intersections.

Right turns have been operated 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, various movements can be assigned 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 figure 34. The overlap forms a separate movement that derives 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 nonconflicting left-turn phase from the cross street). During a transition between two parent phases, the overlap will remain green. To

implement this type of true overlap, a three-section head with limited visibility must be used, as the right-turn display may be different from the adjacent through phase.

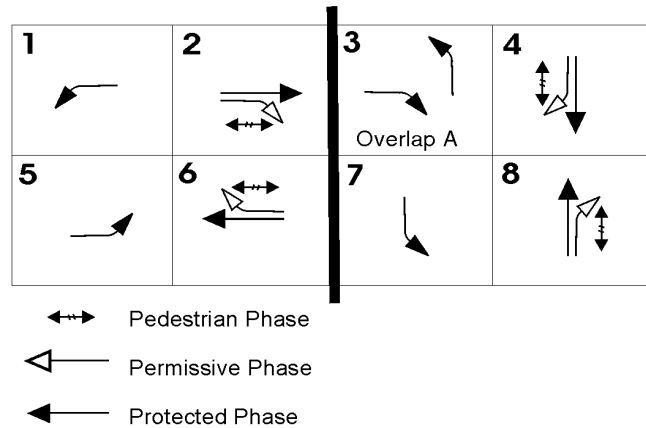
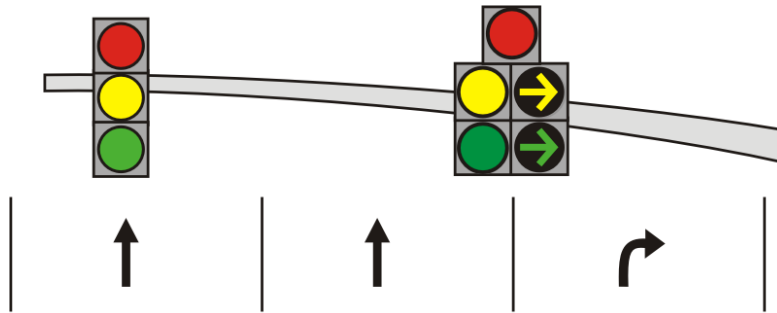
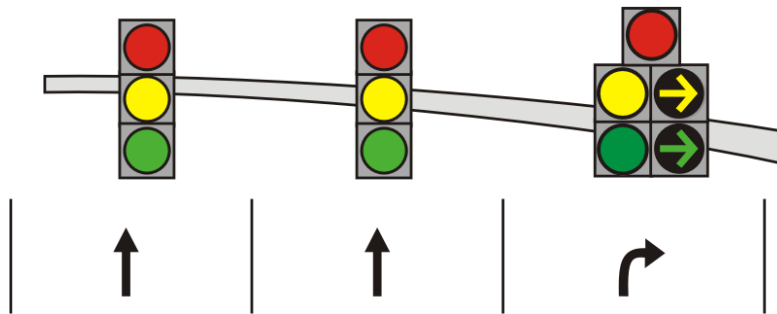


Figure 34. Typical phasing diagram illustrating a right-turn overlap.

More commonly, a five-section head with a combination of circular and arrow indications is 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 nonconflicting left-turn phase on the cross street and the circular indications to the same phase as the adjacent through movement. A typical five-section signal head that implements protected-permissive right-turn phasing is shown in figure 35; refer to the MUTCD for other configurations.



(a) Right-turn overlap phasing using a five-section head located directly above the lane line that separates the exclusive through and exclusive right-turn lane.



(b) Right-turn overlap phasing using a five-section signal head centered above the right-turn lane.

Figure 35. Common signal head and signing arrangements for right-turn-overlap phasing.

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 green ball 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.

4.3 VEHICLE AND PEDESTRIAN DISPLAYS

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

4.3.1 Vehicle Displays

The location of signal heads should be evaluated based on visibility requirements and type of signal display. While signal head placement is governed by MUTCD requirements for signal displays (discussed earlier in this chapter), the specific placement of signal heads is typically determined by local policies. When designing the placement of signal heads, the following should be considered in addition to the minimum requirements described in the MUTCD:

- Consistency with other intersections in the area.
- A geometric design issue that could confuse a driver.

- A large 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.

At large signalized intersections, the safety and operation of the intersection may be enhanced through the use of additional signal heads, some of which are standard in some States. Figure 36 shows a typical intersection design with five types of optional heads:

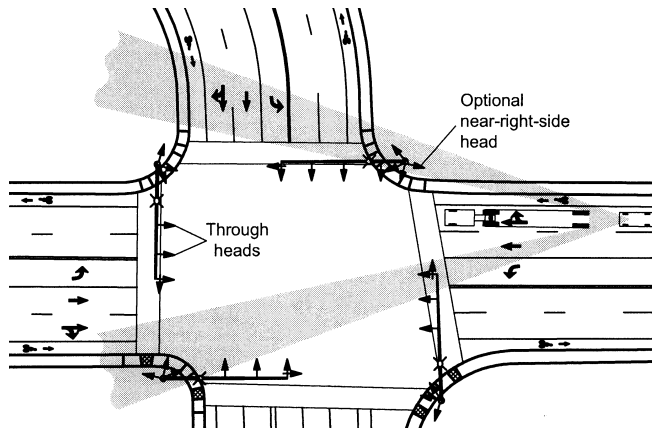
Optional Head #1: This is a near-right-side side head that can be used to provide an advanced head at wide intersections as well as provide a supplemental head for vehicles that are unable to see the signal heads over the lanes due to their position behind large vehicles (trucks, etc.).

Optional Head #2: This is an extra through head that can be used to supplement 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.

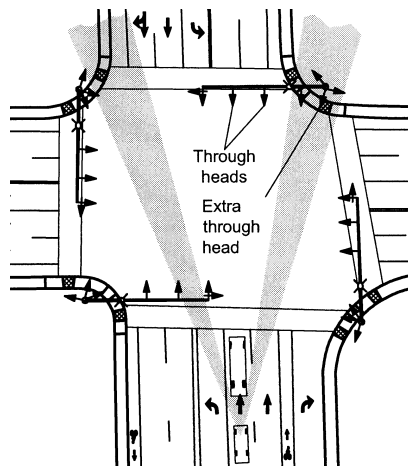
Optional Head #3: This is an extra left-turn head that can be used to guide left-turning vehicles across a wide intersection as they make their turn. It also helps visibility for vehicles behind large vehicles and for times of day when the sun is near the horizon.

Optional Head #4: This is a near-left-side head that can be used to provide an advance indication if visibility is hampered by a curve in the road upstream of the intersection.

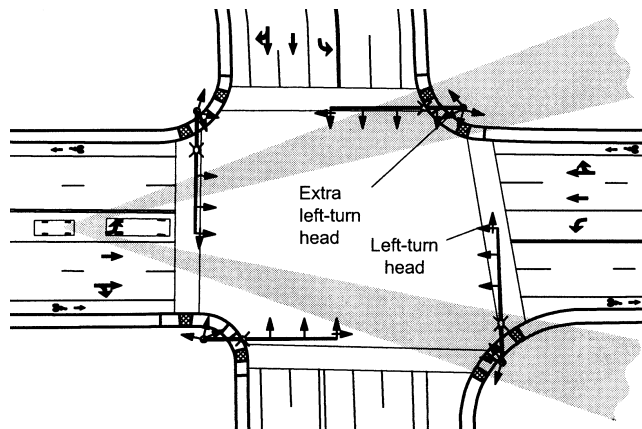
Optional Head #5: This is a head that can be used to provide a display in direct view of a right-turn lane and can also be used to provide a right-turn overlap phase in conjunction with the nonconflicting left-turn phase on the cross street. The head should contain either three circular balls or be a five-section head with three balls and two right-turn arrows due to the concurrent pedestrian crossing.



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

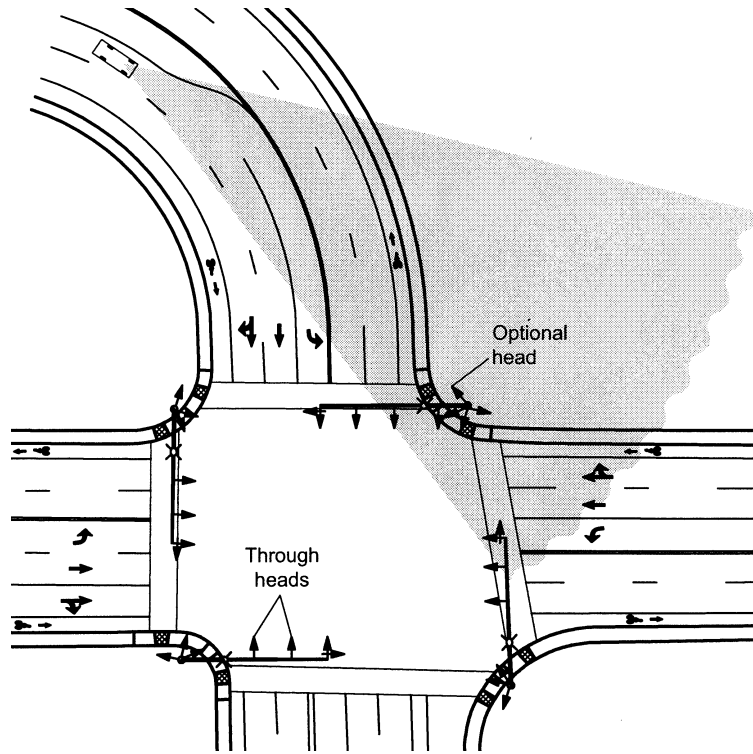


(b) Optional Head #2: Far-side supplemental head for through vehicles.

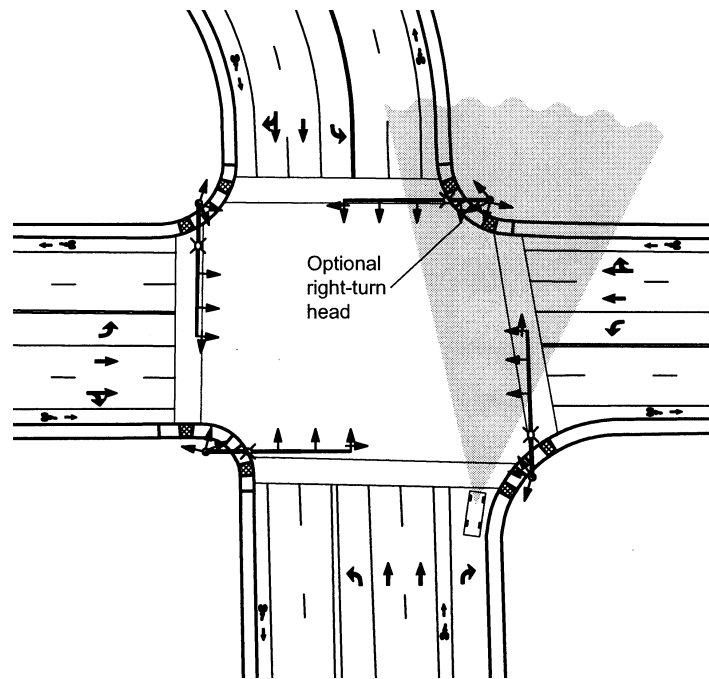


(c) Optional Head #3: Far-side supplemental head for left-turning vehicles.

Figure 36. 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.

Figure 36. Examples showing five optional signal head locations, continued.

4.3.2 Pedestrian Displays

According to section 4E.03 of the 2003 MUTCD, pedestrian signal heads must 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 either 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 should use the UPRaised HAND (symbolizing DON'T WALK) and WALKING PERSON (symbolizing WALK) indications, shown in figure 37. The pedestrian displays must be mounted so that the bottom of the pedestrian signal display housing (including mounting brackets) is no less than 2.1 m (7 ft) and no more than 3 m (10 ft) above sidewalk level.⁽¹⁾



Figure 37. Pedestrian signal indications.

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.06), these factors include:⁽¹⁾

- Increasingly quiet cars.
- Right turn on red (which masks 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.

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. Detail 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).^(51,52,53)

4.4 TRAFFIC SIGNAL POLE LAYOUT

Three primary types of signal configurations display vehicle signal indications:

- Pedestal or post-mounted signal displays.
- Span-wire configurations.
- Mast arms.

Table 13 identifies the advantages and disadvantages of each configuration.

Table 13. Advantages and disadvantages of various configurations for displaying vehicle signal indications.

Advantages	Disadvantages
Pedestal (post-mounted) vehicle signal <ul style="list-style-type: none"> • Low cost • Less impact on view corridors • Lower maintenance costs • Esthetics 	<ul style="list-style-type: none"> • Difficult to meet MUTCD visibility requirements, particularly at large signalized intersections
Span wire vehicle signal <ul style="list-style-type: none"> • Can accommodate large intersections • Flexibility in signal head placement • Lower cost than mast arms 	<ul style="list-style-type: none"> • Higher maintenance costs • Wind and ice can cause problems • May be considered aesthetically unpleasing
Mast arm vehicle signal <ul style="list-style-type: none"> • Provides good 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

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 3.0 m (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,⁽³³⁾ and the AASHTO *Roadside Design Guide*⁽⁵⁴⁾ 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 possible, not conflict with the pedestrian walking paths, and be located for easy access to the pushbuttons by disabled 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.

4.5 TRAFFIC SIGNAL CONTROLLER

The traffic controller is the brain of the intersection. There are two general categories of traffic signal controllers: pre-timed and actuated. In the past two decades, most electro-mechanical and early solid-state controllers have been replaced with NEMA, 170, and advanced traffic controllers (ATC), even in locations where the signal is operated in a pre-timed mode. Although most modern controllers can perform the functions needed at typical signalized intersections, some may not be able to handle: more complicated configurations (e.g., intersections with more than four legs or two closely spaced intersections); communications with other controllers of dissimilar brands; or accommodation of priority treatments (e.g., transit priority). Therefore, the choice of controller may play a significant role in the types of treatments that can be considered at a signalized intersection.

Traffic controllers can be generally classified into three types:

1. NEMA.
2. Type 170.
3. ATC.

Some advantages and disadvantages of each type are described in table 14.

Table 14. Traffic signal controller advantages and disadvantages.

Advantages	Disadvantages
<p>NEMA Controller</p> <ul style="list-style-type: none"> • Specific vendor software • Reduced software/hardware problems 	<ul style="list-style-type: none"> • Cabinets are not standardized • Proprietary software • Proprietary features may not be interchangeable with other NEMA controllers • Typically require larger cabinets • May require extra spare parts if different models exist within one jurisdiction
<p>Type 170 Controller</p> <ul style="list-style-type: none"> • Standard layout and design • Many software choices • More easily adapted to special applications (i.e., ramp metering and Intelligent Transportation Systems (ITS)). • Reduced spare parts inventory 	<ul style="list-style-type: none"> • Software and hardware compatibility problems • Software can be expensive • Liability can be greater with separate software/hardware vendors
<p>Advanced Traffic Controllers (ATC and 2070)</p> <ul style="list-style-type: none"> • Compatible with the National Transportation Communications for ITS Protocol (NTCIP) • Much faster processing speeds • Additional phase inputs • Flexibility for ITS applications 	<ul style="list-style-type: none"> • Lack of proven software • Expensive • Current variations may not be interchangeable

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 that is less likely to be struck by an errant vehicle and where it does not impede 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.

4.6 DETECTION DEVICES

The detectors (or sensors) at an intersection inform the signal controller that a vehicle, pedestrian, or bicycle is present at a defined location within the intersection or signal system. The controller then uses this information to determine the amount of green time and the signal phases to serve.

4.6.1 Vehicle Detection

Table 15, excerpted from the final draft of the *Traffic Detector Handbook*, 2003 edition, presents an overview of the strengths and weaknesses of commercially available detector technology.⁽⁵⁵⁾ The good performance of in-roadway detectors such as inductive loops, magnetic, and magnetometer detectors is based, in part, on their close location to the vehicle, which makes them insensitive to inclement weather due to a high signal-to-noise ratio. Their main disadvantage is their in-roadway installation, necessitating physical changes in the roadway as part of the installation process. In addition, in-roadway detectors may be damaged or disrupted by utility cuts, pavement milling operations for resurfacing, and movement of pavement joints and cracks. Over-roadway detectors often provide data not available from in-roadway sensors, and

some can monitor multiple lanes with one unit. The reader is encouraged to refer to the *Traffic Detector Handbook* for further discussion on detector technology.

Vehicle detectors provide advanced detection, left-turn lane presence detection, and stop-bar presence detection. Advanced detection extends a green signal to get an approaching vehicle through the signal. Left-turn lane presence detection detects left-turning vehicles that are waiting. Stop-bar presence detection will pick up any vehicles that may have entered to roadway from driveways and vehicles that might not have made it though the intersection on the previous green.

A fourth detector function is as a system detector. On many large streets with coordinated signal systems, system detectors are used to collect midblock vehicle volume and occupancy data, which is analyzed by a master signal controller or central system to determine whether signal timing changes are needed. The location of the system detectors varies based on the signal system and software being used, but typically they are located downstream of the intersection on the major roadway.

The location of the advanced detectors is often based on the dilemma zone boundary. The dilemma zone is that portion of the approach where a driver suddenly facing a yellow indication must make a decision whether to stop safely or to proceed through the intersection. As a result, the dilemma zone boundary is typically dictated by the minimum stopping distance. The actual distances vary by jurisdictional policies and should be reviewed before the traffic signal is designed. The typical location for advance detectors based on stopping sight distance is shown in table 16.

Table 15. Strengths and weaknesses of commercially available detector technologies.

Technology	Strengths	Weaknesses
Inductive Loop	<ul style="list-style-type: none"> • Flexible design to satisfy large variety of applications • Mature, well understood technology • Large experience base • Provides basic traffic parameters (e.g., volume, presence, occupancy, speed, headway, and gap) • Insensitive to inclement weather such as rain, fog, and snow • Provides best accuracy for count data as compared with other commonly used techniques • Common standard for obtaining accurate occupancy measurements • High frequency excitation models provide classification data 	<ul style="list-style-type: none"> • Installation requires pavement cut • Improper installation decreases pavement life • Installation and maintenance require lane closure • Wire loops subject to stresses of traffic and temperature • Multiple detectors usually required to monitor a location • Detection accuracy may decrease when design requires detection of a large variety of vehicle classes • Destroyed by utility cuts or pavement milling operations
Magnetometer (two-axis fluxgate magnetometer)	<ul style="list-style-type: none"> • Less susceptible than loops to stresses of traffic • Insensitive to inclement weather such as snow, rain, and fog. • Some models transmit data over wireless radio frequency (RF) link 	<ul style="list-style-type: none"> • Installation requires pavement cut • Improper installation decreases pavement life • Installation and maintenance require lane closure • Models with small detection zones require multiple units for full lane detection
Magnetic (induction or search coil magnetometer)	<ul style="list-style-type: none"> • Can be used where loops are not feasible (e.g., bridge decks) • Some models are installed under roadway without need for pavement cuts, but boring under roadway is required • Insensitive to inclement weather such as snow, rain, and fog. • Less susceptible than loops to stresses of traffic 	<ul style="list-style-type: none"> • Installation requires pavement cut or tunneling under roadway • Cannot detect stopped vehicles unless special sensor layouts and signal processing software are used
Microwave Radar	<ul style="list-style-type: none"> • Typically insensitive to inclement weather at the relatively short ranges encountered in traffic management applications • Direct measurement of speed • Multiple lane operation available 	<ul style="list-style-type: none"> • Continuous Wave (CW) doppler sensors cannot detect stopped vehicles

Source: Adapted from reference 55.

Table 15. Strengths and weaknesses of commercially available sensor technologies, continued.

Technology	Strengths	Weaknesses
Active Infrared (laser radar)	<ul style="list-style-type: none"> • Transmits multiple beams for accurate measurement of vehicle position, speed, and class • Multiple-lane operation available 	<ul style="list-style-type: none"> • Operation may be affected by fog when visibility is less than ~6 m (20 ft) or blowing snow is present • Installation and maintenance, including periodic lens cleaning, require lane closure
Passive Infrared	<ul style="list-style-type: none"> • Multizone passive sensors measure speed 	<ul style="list-style-type: none"> • Passive sensor may have reduced vehicle sensitivity in heavy rain, snow, and dense fog • Some models not recommended for presence detection
Ultrasonic	<ul style="list-style-type: none"> • Multiple-lane operation available • Capable of overheight vehicle detection • Large Japanese experience base 	<ul style="list-style-type: none"> • Environmental conditions such as temperature change and extreme air turbulence can affect performance; temperature compensation is built into some models • Large pulse repetition periods may degrade occupancy measurement on freeways with vehicles traveling at moderate to high speeds
Acoustic	<ul style="list-style-type: none"> • Passive detection • Insensitive to precipitation • Multiple lane operation available in some models 	<ul style="list-style-type: none"> • Cold temperatures may affect vehicle count accuracy • Specific models are not recommended with slow moving vehicles in stop-and-go traffic
Video Image Processor	<ul style="list-style-type: none"> • Monitors multiple lanes and multiple detection zones/lanes • Easy to add and modify detection zones • Rich array of data available • Provides wide-area detection when information gathered at one camera location can be linked to another 	<ul style="list-style-type: none"> • Installation and maintenance, including periodic lens cleaning, require lane closure when camera is mounted over roadway (lane closure may not be required when camera is mounted at side of roadway) • Performance affected by inclement weather such as fog, rain, and snow; vehicle shadows; vehicle projection into adjacent lanes; occlusion; day-to-night transition; vehicle/road contrast; and water, salt grime, icicles, and cobwebs on camera lens • Requires 15- to 21-m (50- to 70-ft) camera mounting height (in a side-mounting configuration) for optimum presence detection and speed measurement • Some models susceptible to camera motion caused by strong winds or vibration of camera mounting structure • Generally cost-effective when many detection zones within the camera field-of-view or specialized data are required

Source: Adapted from reference 55.

Table 16. Location of advanced vehicle detectors.

Speed	Calculated Stopping Distance	Single Detector Setback	Multiple Detector Setback	
			10% Probability of Stopping	90% Probability of Stopping
33 km/h (20 mph)	22.0 m (72.2 ft)	21 m (70 ft)	—	—
40 km/h (25 mph)	31.8 m (104.4 ft)	32 m (105 ft)	—	—
48 km/h (30 mph)	42.9 m (140.8 ft)	43 m (140 ft)	—	—
56 km/h (35 mph)	55.7 m (182.9 ft)	56 m (185 ft)	31 m (102 ft)	77 m (254 ft)
64 km/h (40 mph)	70.4 m (231.0 ft)	70 m (230 ft)	37 m (122 ft)	87 m (284 ft)
72 km/h (45 mph)	86.5 m (283.8 ft)	*	46 m (152 ft)	100 m (327 ft)
80 km/h (50 mph)	104.2 m (341.9 ft)	*	52 m (172 ft)	108 m (353 ft)
88 km/h (55 mph)	123.8 m (406.3 ft)	*	71 m (234 ft)	118 m (386 ft)

* Use multiple detectors or volume-density modules.

Source: (Reference 56 (table 7-1); reference 57 (table 4-3); metric values converted from U.S. customary provided in sources)

As shown in table 16, the stopping distance can be computed for both the average stopping condition as well as the probability ranges for stopping. For most large intersections, a multiple-loop design should be used to account for the higher speeds and probabilities of stopping. More detailed information on detector placement, including the results of several calculation methods, can be found in the *Manual of Traffic Detector Design*.⁽⁵⁸⁾

4.6.2 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 and located as follows (sections 4E.08 and 4E.09):⁽¹⁾

- Adjacent to a level all-weather surface to provide access from a wheelchair with a wheelchair-accessible route to the ramp.
- Within 1.5 m (5 ft) of the crosswalk extended.
- Within 3 m (10 ft) of 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 3 m (10 ft).
- Mounted at a height of approximately 1.1 m (3.5 ft) above the sidewalk.

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*.⁽³⁵⁾

4.7 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 the determination of 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.

4.7.1 Pedestrian Timing

Pedestrian timing requirements include a WALK interval and a flashing DON'T WALK interval. The WALK interval varies based upon local agency policy. The MUTCD recommends a minimum WALK time of 7 s, although WALK times as low as 4 s may be used if pedestrian volumes and characteristics do not require an interval of 7 s (section 4E.10).⁽¹⁾ The WALK interval gives pedestrians adequate time to perceive the WALK indication and depart the curb before the clearance interval (flashing DON'T WALK) 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 time 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 before opposing vehicles receive a green indication. The MUTCD uses a walk speed of 1.2 m/s (4.0 ft/s) for determining crossing times.⁽¹⁾ However, the *Pedestrian Facilities Users Guide* recommends a lower speed of 1.1 m/s (3.5 ft/s); see chapter 2 for further discussion.⁽³⁵⁾ Pedestrian clearance time is calculated using equation 1:

$$\text{Pedestrian Clearance Time} = \frac{\text{Crossing Distance}}{\text{Walking Speed}} \quad (1)$$

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 typically 1.2 m/s (4 ft/s) or 1.1 m/s (3.5 ft/s) as indicated above.

Pedestrian clearance time is accommodated during either a combination of flashing DON'T WALK time and yellow clearance time or by flashing DON'T WALK time alone. The recommended practice is for the pedestrian clearance time to be accommodated completely within the flashing DON'T WALK time. However, 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.

4.7.2 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.

The minimum green time is the amount of time allocated to each phase so that vehicles in queue at the stop bar are able to start and clear the intersection. The minimum initial green time is established by determining the time needed to clear the vehicles located between the stop bar and the detector nearest the stop bar. Where presence detection is installed at the stop bar, a minimum interval may be set to a value that is less than 1.0 s.

Consider an intersection with the following properties: average vehicle spacing is 7.5 m (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 30 m (100 ft) from the stop bar, the minimum green time is $2 + (30 \text{ m}/7.5 \text{ m} \times 2) = 2 + (100 \text{ ft}/25 \text{ ft} \times 2) = 10 \text{ s}$.

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. The maximum green time begins when a

call is placed on a conflicting phase. The phase is allowed to "max-out" if the maximum green time is reached even if actuations have been received that would typically extend the phase.

4.7.3 Vehicle Timing—Detector Timing

One advantage of actuated control is that it can 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 timing. More information about detector timing, including settings for various detector configurations, is found in the FHWA *Traffic Detector Handbook*.⁽⁵⁵⁾

One type of detector timing, known as volume-density timing, 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.

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. The one phase that is the exception is the coordinated phase, which receives the unused or additional time.

4.7.4 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):

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

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 s, 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 s to 6 s and that the red clearance interval should not exceed 6 s (section 4D.10).⁽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. For this reason, red light photo enforcement should not be used during the period of red clearance required by the ITE formula.

Current thought is that longer clearance intervals will cause drivers to enter the intersection later and will breed 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.⁽⁵⁹⁾ Additional research is needed to examine the effect of lengthening the yellow interval on driver behavior.

4.7.5 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, it is preferred that the cycle lengths for conventional, four-legged intersections not exceed 120 s, although larger intersections may require longer cycle lengths. Longer cycle lengths generally result in increased delay and queues to all users, particularly minor movements. There may also be a connection between longer cycle lengths and increased incidence of red-light running, although this has not been documented in research. Although longer cycle lengths result in fewer change periods per hour and thus fewer opportunities for red-light running, more drivers may be tempted to run the red light to avoid the extra delay caused by the longer cycle length.⁽⁶⁰⁾

4.8 SIGNING AND PAVEMENT MARKING DESIGN

Signs and pavement markings are important elements of the design of an intersection. 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 FHWA's MUTCD⁽¹⁾ is the primary reference for use in the design and placement of signs and pavement markings. Additional resources include State supplements to the MUTCD and reference materials such as ITE's *Traffic Control Devices Handbook* (TCDH)⁽⁶¹⁾ and *Traffic Signing Handbook*.⁽⁶²⁾

Designing effective signing and pavement marking at high-volume signalized intersections in particular 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 are also frequently in urban areas where other intersections, driveways, and urban land use

create visibility conflicts. The following questions, adapted from the ITE *Traffic Signing Handbook*⁽⁶²⁾, represent a basic thought process that is 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 at the intersection provided? Is advance street name information (“XX Street, Next Signal,” etc.) and (if appropriate) route number directional signage provided in advance of the intersection? Figure 38 gives an example of a simple advance street name sign on approach to an intersection, and figure 39 gives an example of an advance sign that provides street names for the next two signalized intersections.



Figure 38. Example of advance street name sign for upcoming intersection.



Figure 39. 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, trap lanes, and right-hand exits for left turns are all examples where driver expectancy is violated and should be addressed by signing. Figure 40 shows an example of signage used to advise motorists of a trap lane.



Figure 40. Example of signing for a left-hand lane trap.

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, signage is needed to convey this message to the user. Figure 41 provides an example of an overhead signs used to assist drivers in selecting the proper lane on approach to a signalized intersection.



Figure 41. Example of advance overhead signs 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 be easily comprehended and attended 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. This may, for example, lend itself to the use of overhead signs in advance of large intersections, as well as large retroreflectorized or internally illuminated overhead signs (including street name signs) at 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, warning, 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 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 signage”) may be used to supplement signing for this purpose, as shown in figure 42.



Figure 42. Example of pavement legends indicating destination route numbers (“horizontal signage”)

4.9 ILLUMINATION DESIGN

As noted in *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.”^(63, p.1)

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)⁽⁶³⁾ 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.

4.9.1 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 the lighting of intersections 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.⁽⁶³⁾

Table 17 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).

Table 18 presents the roadway and pedestrian area classifications used for determining the appropriate illuminance levels in table 17. RP-8-00 clarifies that although the definitions given in table 18 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 table 18 (section 2.0, p. 3).⁽⁶³⁾

4.9.2 Veiling Luminance

Veiling luminance is produced by stray light from light sources within the field of view. 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 (annex C).⁽⁶³⁾ Table 17 shows the maximum veiling luminance required for good intersection lighting design.

Table 17. Recommended illuminance for the intersection of continuously lighted urban streets.

Pavement Classification ²	Roadway Classification	Average Maintained Illuminance at Pavement ¹			Uniformity Ratio (Eavg/Emin) ³	Veiling Luminance Ratio (Lvmax/Lavg) ⁴
		Pedestrian/Area Classification				
		High (lux (fc))	Medium (lux (fc))	Low (lux (fc))		
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

Notes: ¹ fc = footcandles

² R1 is typical for portland cement concrete surface; R2/R3 is typical for asphalt surface.

³ Eavg/Emin = Average illuminance divided by minimum illuminance

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

Source: Reference 63, table 9 (for R2/R3 values); R1 values adapted from table 2.

Table 18. 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 Volumes²
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 200 m (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 63, sections 2.1, 2.2, and 3.6