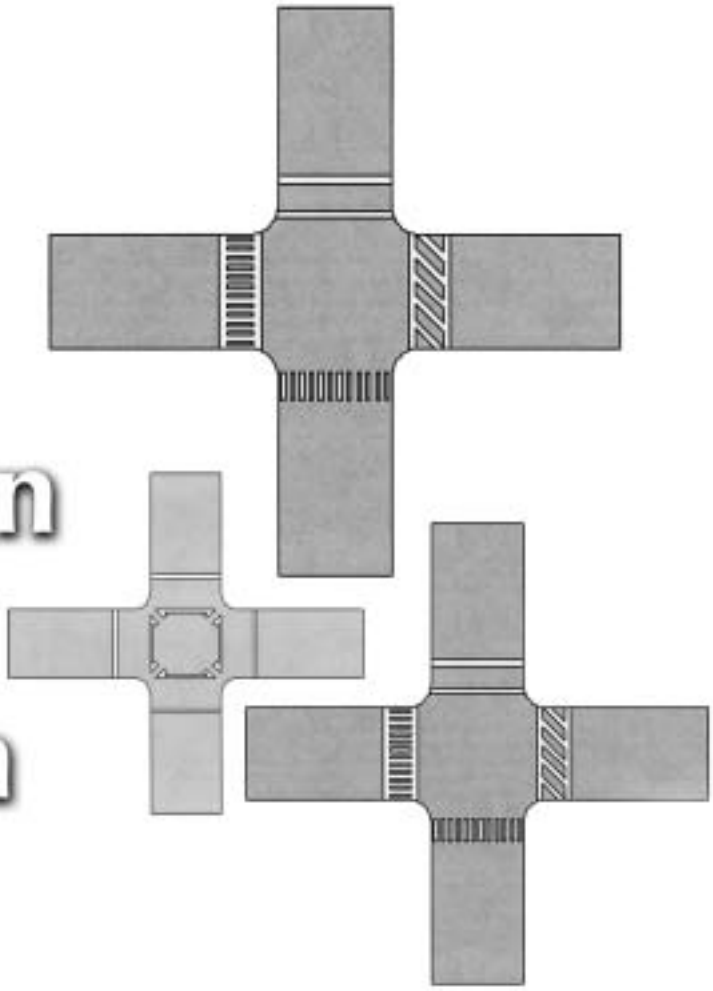
Toolbox on Intersection Safety and Design



Institute of Transportation Engineers

U.S. Department of Transportation
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Toolbox on Intersection Safety and Design

An Informational Report of the
Institute of Transportation Engineers

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chapter one

Introduction

1.1 Purpose

The purposes of this report are to (1) demonstrate practical design measures and tools that will improve intersection safety and operations for all users of the roadway, (2) provide examples of effective applications and (3) discuss experiences with innovative solutions. Many of these measures, tools, applications and innovative solutions were presented and discussed during the ITE 2004 Technical Conference and Exhibit, "Intersection Safety: Achieving Solutions Through Partnerships."

The intended audience is any person with an interest in or responsibility for intersection safety and operational issues facing urban, rural and neighborhood communities. It is expected that this report will help readers develop intersection designs that achieve the highest levels of safety, mobility and cost-effectiveness.

An important, though secondary, purpose of this report is to improve awareness of intersection safety and design literature. The technical chapters are not intended to rehash existing design publications or references, or summarize existing intersection design criteria. The reader is provided ample information to locate appropriate resources.

Finally, it is recognized that the topic of intersection design and safety is broad and it is unrealistic to include the countless number of federal, state and local policies, standards and guidelines in a single report. Similarly, it is not possible to include the full breadth of personal views, ideas, perspectives, philosophies and expectations related to intersection design and performance. It is, therefore, incumbent upon the reader to view the ideas presented within the context of the needs and expectations of his/her local area, as well as the latest practice standards, guidelines and research developments in this field.

1.2 The Intersection Safety Problem

Specific designs of individual intersections* can vary significantly from location to location based on the alignment and functional classification of the intersecting roadways, the type and amount of traffic the roadways are expected to carry and the land use characteristics in the vicinity of the intersection. The intersection design should permit all users to clearly see and be seen by other users of the intersection, enable timely understanding of directions of travel and rights-of-way, be clear of unexpected hazards and consistent with the roadway or pathway on the intersection approach. Despite the number of factors that can influence intersection design, the design goal is always the same:

maximize both the efficiency and safety of traffic operations within the intersection for all users.

Given that goal, it is sobering to realize that "in 2002, more than 9,000 Americans died and roughly 1.5 million Americans were injured in intersection-related crashes.[2] In economic terms, intersection-related crashes in the year 2000 cost about $40 billion.[3]

1.2.1 Motor Vehicles

The frequency, type and severity of motor vehicle collisions that occur at intersections can vary by location. The most common types of intersection crashes are crossing collisions when one vehicle strikes the side of another, rear-end collisions and sideswipe accidents resulting from improper lane changes. Factors such as traffic volume and speed, percentage of turning vehicles, geometric design, weather and lighting conditions and traffic control all play significant roles in the safety conditions at an intersection.

1.2.2 Pedestrians

Crashes at intersections that involve pedestrians are a significant concern. Approximately 35 percent of crashes and fatalities involving pedestrians occur at intersection locations.[4] However, this percentage changes with the age of the pedestrian. Signalized intersections can be especially hazardous for older pedestrians. "An analysis of 5,300 pedestrian crashes at urban intersections indicated that a significantly greater proportion of pedestrians age 65 and older were hit at signalized intersections than any other group.[5]

1.2.3 Bicyclists

Bicycle crashes at intersections constitute approximately one-third of all reported crashes involving bicyclists. A problem with attempting to understand the nature of bicycle-related crashes is that only an estimated 10 percent are reported. These bicycle incidents usually involve motor vehicles, but can also include encounters with other bicyclists, pedestrians and objects, including the ground. Many factors related to bicyclist crashes and fatalities are relevant to intersection locations and include:

- Failure to yield to right-of-way;
- Improper intersection crossing maneuvers;
- Failure to obey traffic control devices;
- Performing improper turns; and
- Failure to display proper lighting at night.

Bicyclists were judged to be at fault in approximately 50 percent of crashes with motor vehicles and nearly 70 percent of the motorists reported they did not see the bicyclist before the collision.

1.3 Organization of Report

Chapter 2 defines the characteristics and needs of all intersection users: motorists, pedestrians, bicyclists and others, including scooters, skates and the Segway.

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* The American Association of State Highway and Transportation Officials (AASHTO) defines an intersection as "the general area where two or more highways join or cross, including the roadway and roadside facilities for traffic movements within the area." According to AASHTO, the main objective of intersection design is to "facilitate the convenience, ease and comfort of people traversing the intersection while enhancing the efficient movement of motor vehicles, buses, trucks, bicycles and pedestrians.[1]

Chapter 3 presents methodologies for the collection, management and analysis of intersection safety data, which will facilitate the identification and understanding of safety problems.

Chapter 4 addresses the specific needs of pedestrians and bicyclists at intersections. Many of the design and operational elements covered in this chapter are supplemented with material presented in Chapters 5–7. Appropriate cross-references enable the reader to gather the complete picture of effective applications and tools. These chapters also address geometric design, traffic control devices and traffic signal elements of intersection design, respectively. Because many features require complementary applications from the other elements of intersection design, guidance in these chapters is cross-referenced with other chapters in this report as needed.

Chapter 8 presents an overview of safety and design issues for roundabouts.

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chapter two

Characteristics and Needs of Intersection Users

Each person that passes through an intersection should be accommodated at a reasonable level of safety and efficiency. Therefore, an effective and safe intersection design requires that the characteristics, requirements and needs of all intersection users be understood. Design guidelines that provide the recipe for meeting this mandate are regularly updated. There are many recent examples of how design considerations, such as controlling vehicle speeds, minimizing exposure and conflict points, increasing visibility, reducing attention demands and separating modes have led to successful design practices. These experiences continue to demonstrate that motorists, pedestrians, bicyclists and other users can coexist efficiently and safely.

This chapter presents a sampling of the user characteristics that must be understood. These characteristics include physical attributes (for example, visual acuity, walking speed) as well as cognitive capabilities (understanding of traffic signal indications). Resources for a more complete understanding of user characteristics are also provided.

2.1 Motorists

Design and operation standards implicitly accommodate the physical characteristics and cognitive capabilities of motorists. Nevertheless, an awareness of the explicit characteristics of motorists can help in the development of effective and safe intersection designs. A limited set of sample characteristics is presented below as an illustration of importance.

2.1.1 Physical Characteristics

The physical ability and likelihood of a motorist to see traffic control devices and potential conflicts is addressed as part of the intersection design process.

Driving is a "dynamic visual-motor task. The visual scene and the information from it are continually changing as one proceeds along the road. At high speeds, the information that the driver needs comes into view and must be processed very quickly.[1] Therefore, the proper placement of traffic control devices is a necessary component of success in conveying the appropriate message to a motorist.

For example, when the eye is in a fixed position, the most acute vision area is a cone with an approximate 3° angle left and right. Vision is quite satisfactory within a cone of 5° or 6° and fairly satisfactory up to about 20°. Desirably, a traffic signal indication should be located directly in line with approaching traffic, within the range of satisfactory vision. Signal indications that are farther from the driver's cone of acute vision are less likely to be noticed.

Another physical characteristic is the vehicle being driven, including its length, width, height and comfortable deceleration and acceleration rates. AASHTO defines 19 different design vehicles within four general classifications, including passenger cars, buses, trucks and recreational vehicles.[2] It is not practical to design for all of these vehicles at every intersection. Designers must select a design vehicle(s) that the intersection should accommodate.

The selection of a design vehicle is based on the type of vehicles expected to use the intersection. It is not uncommon, however, to design for more than one design vehicle because the operating characteristics of a range of small and large vehicles need to be taken into account. For most high volume urban roadways, a tractor semi-trailer with a 50-ft. wheelbase (WB-50) is used for designing turning areas. In areas where trucks are prohibited, the use of a passenger car (PC) may be used. However, a single unit truck configuration (SU) or a 40-ft. tractor semi-trailer combination (WB-40) may also be used to permit adequate maneuvering area for emergency, garbage and delivery vehicle operation in the area. Where even this size of maneuvering area is not possible, a designer may design pavement areas large enough to allow movements of the occasional large truck using both lanes of an approach when it is needed for rare, temporary, or emergency circumstances.

2.1.2 Cognitive Capabilities

Once a traffic signal indication has been seen, the motorist must interpret its meaning and make decisions about how to respond. Although the red, yellow and green signal indications are understood by motorists, the driver is still faced with complex decisions when responding to the signal. For example at the onset of the yellow change interval, drivers must quickly assess speed and distance from the intersection and decide whether it is better to brake to a stop or continue through the intersection. This decision must be made with only an estimate of the distance that it would take to stop, the time it would take to continue through the intersection and the length of the phase change interval. Different drivers with different levels of experience, judgment and risk tolerance will make different choices. Signal timing concepts, such as change intervals and dilemma zones, and how they accommodate motorist characteristics are covered in Chapter 7.

Sometimes the issue with cognitive capabilities has to do with a motorist's understanding of the actual traffic control device and its meaning. For example, traffic signals are sometimes operated in the flashing mode during low-volume periods of time or as a result of a signal malfunction. The red/yellow flashing operation is often misunderstood. One study concluded "drivers facing a flashing red indication do not appear to understand that the conflicting traffic may be facing a flashing yellow."[3] In other words, some motorists believe the intersection is operating as a four-way stop and may unwittingly conflict with a non-stopping, through-movement vehicle on the cross street.

2.2 Pedestrians

All people are pedestrians at some point in their daily travel as almost all trips have a pedestrian component. Whether it involves walking to or from a parked vehicle, walking to a specific destination (for example, work, school, shopping), transferring between different modes of transportation, or walking for recreation and exercise, safe and efficient pedestrian travel is critical to the usability of the entire transportation system.

The term *pedestrian* encompasses many different users. A pedestrian includes someone pushing an infant in a stroller, elderly people with walkers, adults using a wheelchair, visually impaired people with guide dogs, children going to school, or even recreational runners. Changes in recreational modes of travel have also broadened the use of the term pedestrian.

2.2.1 Physical Characteristics

Perhaps the most significant physical characteristic of a pedestrian related to intersection safety and design is walking speed. Walking speed for most design practices is considered to be 4.0 ft./sec.[4] However, several documents have recommended the use of lower walking speeds:

- A task force of the National Committee on Uniform Traffic Control Devices and an ITE publication have both recommended that the design walking speed be reduced to 3.5 ft./sec. where slower walking speeds are known to occur (in other words, where significant volumes of older pedestrians, pedestrians with disabilities, or child pedestrians are present).[5,6]
- A walking speed of 3.0 ft./sec. has been recommended when the percentage of elderly pedestrians (persons older than 65 years of age) exceed 20 percent.[7]
- The U.S. Access Board suggests that all pedestrian signal timing design should be calculated using a maximum walking speed of 3.0 ft./sec.[8]
- The *Highway Design Handbook for Older Drivers and Pedestrians*[9] recommends use of a walking speed of 2.8 ft./sec. to accommodate the shorter stride and slower gait of older pedestrians.

Pedestrian walking speeds typically range between 2.5 and 6.0 ft./sec., but walking speeds outside this range are not uncommon. For example, the walking speed of elderly pedestrians with disabilities or of pedestrians on a leisurely walk, can often fall below 2.5 ft./sec. Similarly, recreational walkers and exercise enthusiasts often walk or run at speeds greater than 6.0 ft./sec.

Every effort should be made to meet the needs of all pedestrians, but accommodating the 100th percentile walking speeds may not be prudent or practical. Advanced technologies in pedestrian detection have the potential to allow for real-time variability in pedestrian crossing times (refer to Section 4.1.4.5 in Chapter 4 for a discussion of innovative pedestrian detection applications).

2.2.2 Cognitive Capabilities

In terms of the cognitive capabilities of pedestrians, one study concluded that "about one-third of fatal pedestrian collisions result from pedestrians disobeying intersection traffic control or making dangerous judgments in attempting to cross a street."[10]

Pedestrian signal indications tend to be poorly understood. In a survey of 4,700 people, just under half thought that the flashing DON'T WALK signal meant to return to the curb and 47 percent thought that the WALK signal meant there were no turning vehicle conflicts.[1]

2.3 Pedestrians with Disabilities

An important consideration in the design of intersections is the accommodation of persons with

disabilities. Disabilities can range from ambulatory difficulties requiring various assistive devices or wheelchairs, to visual and various developmental impairments. Reported average walking speeds for pedestrians with various physical conditions are listed in Table 2–1.

Table 2–1: Average Walking Speeds for Various Physical Conditions

Physical Condition	Average Walking Speed (ft./sec.)
Cane/Crutch	2.62
Walker	2.07
Wheelchair	3.55
Immobilized knee	3.50
Hip arthritis	2.24 to 3.66

Source: Ref 11, page 43

Accommodating people with disabilities in intersection design is required by law and enhances the mobility and safety of all pedestrians. Designs that do not include access for all users, including temporary access in short-term conditions, are not acceptable.

2.3.1 Requirements for Accessible Facilities

Federally funded programs have been required to provide accessible features for nearly four decades. The Architectural Barriers Act of 1968 first required new federal facilities to be accessible and Section 504 of the Rehabilitation Act of 1973 required non-discrimination in all federally funded programs. The Americans with Disabilities Act of 1990 (ADA) extends the Section 504 requirements of usability and accessibility to all government programs, including new and altered facilities, regardless of funding source.

The ADA is a landmark civil rights law that both identifies and prohibits discrimination on the basis of disability. The act prohibits discrimination in employment, telecommunications, transportation, access to facilities and programs provided by state and local government entities, and access to the goods and services provided by places of public accommodation such as lodging, health and recreation facilities. People who design and construct facilities are responsible under the ADA to make facilities accessible to and usable by people with disabilities.

The ADA requires consideration of the needs of pedestrians with disabilities as intersections are designed, built, or modified. The implementing regulation of the ADA addresses this in the following statement:[12]

> *"Title II: State and Local Government Services, Subpart D, Program Accessibility, 35.151 New construction and alterations. Each facility constructed by, on behalf of, or for the use of a public entity shall be designed and constructed in such manner that the facility...is readily accessible to and usable by individuals with disabilities."*
>
> *The preamble to Title III at 36.401 General Substantive Requirements of the New Construction Provisions explains that the phrase "readily accessible to and usable by individuals with disabilities" is a term that, in slightly varied formulations, has been used in the Architectural Barriers Act of 1968, the Fair Housing Act, the regulations implementing section 504 of the Rehabilitation Act of 1973 and current accessibility standards. It means, with respect to a facility or a portion of a facility, that it can be approached, entered and used by individuals with disabilities (including mobility, sensory and cognitive impairments) easily and conveniently...To the extent that a particular type or element of a facility is not specifically addressed by the standards, the language of this section is the safest guide.*

Subpart E of Title II regulations discusses effective communications with people with disabilities, which

can be interpreted to apply to signage, pedestrian signals and other communication with the public at intersections.

> *"A public entity shall take appropriate steps to ensure that communications with applicants, participants and members of the public with disabilities are as effective as communications with others."*

Because Americans with Disabilities Act Accessibility Guidelines (ADAAG) do not yet include specific provisions to the public rights-of-way, designers have had to adapt current building standards for use on sidewalks and street crossings in order to meet the law's requirements for accessibility. Until the new standards are completed, designers and engineers must use their own judgment to determine what constitutes accessibility as required by law. The draft guidelines that are available offer some guidance.

2.3.2 Public Rights-of-Way Guidelines

Guidelines addressing specific issues in the public rights-of-way are under development. On June 17, 2002, Draft Public Rights-of-Way Accessibility Guidelines developed by the Access Board were published for public comment.[8] Information pertaining to pedestrian access routes, curb ramps and blended transitions, pedestrian crossings, accessible pedestrian signal (APS) systems, street furniture, detectable warning surfaces, on-street parking, call boxes and alternate circulation paths will be included in the final guidelines. ADAAG establishes the required minimum levels of accessibility. These draft guidelines provide an indication of the requirements that will be established by the Access Board when the proposed rule is published and can be considered the best guidance available until a rule is finalized.

2.4 Bicyclists

Bicyclists require the same safety and mobility afforded to all other users of an intersection. Typically, bicyclists are accommodated within the roadway system and share space with motor vehicles. Only in unique cases are bicyclists encouraged to operate within pedestrian facilities because the potential safety implications of this interaction are undesirable.

For bicyclists, a designated operating space is one of the most important design features and requires a travel width of at least 40 in. to provide comfortable operation.[2, 14] Widths greater than 60 in. are desirable when traffic volumes, vehicle or bicyclist speed, and/or the percentage of truck and bus traffic increases.

The skills, confidence and preferences of bicyclists vary dramatically from one rider to the next. Most adult riders have moderate levels of confidence and prefer to use facilities, such as dedicated bicycle lanes or shared-use paths, with a comfortable amount of operating space away from motor vehicles. Although children are often confident and possess very good bicycle handling skills, they typically do not possess the traffic awareness and experience of adult riders. Few bicyclists are confident riding on busy and high-speed roadways alongside motorized traffic that have few, if any, special accommodations for bicyclists.

The Federal Highway Administration (FHWA) categorizes bicycle user types to assist roadway designers in determining the impact of different facility types and roadway conditions on bicyclists:[15]

- Advanced (A) or experienced riders generally ride for convenience and speed and desire direct access to destinations with minimum detour or delay. They are comfortable riding with motor vehicle traffic. However, they still require sufficient operating space on the traveled way or shoulder to eliminate the need for position shifting by either a passing vehicle or bicyclist.

- Basic (B) or less confident adult riders may also use bicycles for transportation purposes, but prefer to avoid roads with high volumes of motor vehicle traffic unless there is ample roadway width to enable 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 bicycle-only or wide shoulder lanes when traveling with heavier motor vehicle traffic.
- Although children (C), riding on their own or with their parents, may not travel as fast as their adult counterparts, they still require access to key destinations within a community such as schools, convenience stores and recreational facilities. Residential streets with low vehicle speeds, linked together by shared-use paths and busier streets with well-defined pavement markings between bicycles and motor vehicles lanes, can accommodate children without encouraging them to ride in major arterial travel lanes. A common objective for bicycle facility planning purposes is to try to accommodate both A and C bicyclists, which likely requires both on- and off-street facilities.

For detailed information on specific bicyclist characteristics, the reader is referred to the AASHTO *Guide for the Development of Bicycle Facilities*[14] and *Innovative Bicycle Treatments*, published by ITE.[16]

2.5 Other Modes

2.5.1 Transit

Public transit, including buses and light rail systems, is another potential user of the intersection infrastructure that must be considered. Intersections are often desirable locations for mode-transfer locations (for example, transit stops) that typically require associated pedestrian, bicycle and in some cases, park-n-ride facilities. Transit vehicles that share operating space with other roadway vehicles offer a unique set of variables to intersection design and safety, such as the accommodation of transit vehicle stopping locations that do not significantly impact vehicle operations. Several publications provide a detailed overview of transit facilities at intersections. Transit Cooperative Research Program (TCRP) report *Location and Design of Bus Stops on Major Streets and Highways* is an excellent resource for design guidance on bus stop facilities.[17] The Federal Transit Agency (FTA) also has links to other references.[18]

2.5.2 Other Users

Many other transportation system users exist that are too variable to classify into a single group. Some of these people use scooters, skates (in-line and roller), or skateboards, which are all commonplace at intersections nationwide. Even the contemporary Segway Human Transporter is becoming more prevalent. A question arises when considering facility design and operations: should these users be classified as pedestrians, bicyclists, or neither? Because no specific standards exist and very little research has been performed, universally accepted answers to this question are not available.

2.6 Variability in Right-of-Way Laws

Although there are a number of generally accepted guidelines, policies and standards, there is no national traffic law in the United States. Each state has created individual laws concerning the users in the operation of the transportation system, which has led to considerable variability. The Uniform Vehicle Code, developed by the National Committee on Uniform Traffic Laws and Ordinances (NCUTLO), provides a model law that most states have adopted in some form.[19] It is interesting to note that the vehicle codes regulate people in the form of pedestrians and drivers, not vehicles. The definition of pedestrian is consistent in most publications. Drivers are defined as those operating any kind of wheeled vehicle or animal on any part of the roadway system.

Right-of-way laws and the definition of various users differ significantly from state to state. For example, Wisconsin state law defines a pedestrian as "any

person afoot or any person in a wheelchair, either manually or mechanically propelled, or other low-powered, mechanically propelled vehicle designed specifically for use by a physically disabled person, but does not include any person using an electric personal assistive mobility device."[20] A bikeway is defined as "a public path, trail, lane, or other way, including structures, traffic control devices and related support facilities and parking areas, designed for use by bicycles, electric personal assistive mobility devices and other vehicles propelled by human power." Bicycle lanes are "that portion of a roadway set aside by the governing body of any city, town, village, or county for the exclusive use of bicycles, electric personal assistive mobility devices, or other modes of travel permitted and so designated by appropriate signs and markings."

Bicyclists are considered "drivers of vehicles" in every state.[21] Beyond this consideration, there is little consistency. States do not agree on the definition of a bicycle or on operation and visibility rules. An interesting distinction is how states view mixing pedestrians and bicyclists on sidewalks. A person who walks a bike is considered a pedestrian in all jurisdictions. Some states have a rule that prohibits drivers from using sidewalks. At least five states include "bicycle" in the definition of "vehicle" and prohibit vehicle use on sidewalks: Arizona, Indiana, Nevada, New Jersey and North Dakota. At least 22 states explicitly permit bicycling on the sidewalks, usually with exceptions. In most of the other states, sidewalk bicycling is implicitly permitted since there is no general prohibition against driving vehicles on sidewalks. Furthermore, signs or local ordinances may prohibit sidewalk bicycling. In Wisconsin, sidewalk bicycling is not permitted unless a local government adopts an appropriate ordinance. Sidewalk bicycling is restricted to areas outside business districts in Alaska, Massachusetts, Maryland, Minnesota, Missouri and Pennsylvania. Hawaii permits sidewalk bicycling only at speeds less than 10 mph. Of the 22 states that explicitly permit bicycling on sidewalks, 12 specify that sidewalk cyclists have the rights and duties of pedestrians. Additional detail on bicycle right-of-way laws and a list of state traffic law Web sites can be found in *Bicycles and the Traffic Law*.[21]

Other right-of-way differences from state to state exist pertaining to travel way versus roadway, unmarked crosswalks and white cane use by pedestrians with visual disabilities. Those responsible for intersection design should consider the applicable state and local laws to ensure that the proper facilities are available to accommodate all intersection users.

An example of the dynamic nature of right-of-way laws is demonstrated in some recent changes in state law. Wisconsin, like many states, has added language to accommodate "electric personal assistive mobility devices (EPAMD)" in its definitions.[20] Such a device is defined as "a self-balancing, 2-nontandem-wheeled device that is designed to transport any one person and which has an electric propulsion system that limits maximum speed of the device to 15 mph or less," also known as a Segway Personal Transporter. Wisconsin is one of at least 40 states that have state laws to accommodate these devices. The problem lies in the fact that many states have different ideas on where Segway use is appropriate. Table 2–2 summarizes the variability in state right-of-way law and accommodations for Segway travel as of March 2004. Note that Segway use is permitted by most states on pedestrian facilities. Use on bicycle facilities is less defined. States with no information provided have not enacted formal legislation permitting use on public ways.

Table 2–2: Variations in Right-of-Way Law for Segway Use

	Segway Permitted On:			Pedestrian Laws Apply	*Additional Comments
	Sidewalks	Bicycle Paths	Roads		
Alabama	Yes	Yes	Yes[a]	—	
Alaska	Yes	Yes	—	—	
Arizona	Yes	No	Yes*	Yes	If sidewalk not available
Arkansas	—	—	—	—	
California	Yes[a]	Yes[a]	Yes[a]	Yes	
Colorado	—	—	—	—	
Connecticut	Yes[b]	No	No[c]	—	
Delaware	Yes	Yes	Yes*[d]	—	On highways ≤ 30 mph
District of Columbia	Yes	No	—	—	
Florida	Yes[a]	Yes[a]	Yes*[a]	—	On streets ≤ 25 mph
Georgia	Yes	No	Yes*	Yes	On streets ≤ 35 mph
Hawaii	Yes	Yes	—	—	
Idaho	Yes	No	—	Yes	
Illinois	Yes[a]	No	Yes	Yes	
Indiana	No	Yes	Yes	—	
Iowa	Yes	Yes	No	—	
Kansas	Yes	No	Yes	Yes	
Kentucky	—	—	—	—	
Louisiana	Yes	Yes	Yes*	—	On streets ≤ 35 mph
Maine	Yes[a]	Yes[a]	Yes*[a]	—	On streets ≤ 35 mph if sidewalk/bike path not available
Maryland	Yes	No	Yes*[a]	—	On streets ≤ 30 mph if sidewalk not available
Massachusetts	—	—	—	—	
Michigan	Yes[e]	No	Yes*[a]	—	On streets ≤ 25 mph
Minnesota	Yes	Yes	Yes*[f]	Yes	On streets ≤ 35 mph if sidewalk not available
Mississippi	Yes	Yes	Yes*	—	Where bicycles are permitted
Missouri	Yes	Yes	Yes*[a]	Yes	On streets ≤ 45 mph
Montana	—	—	—	—	
Nebraska	Yes[c]	Yes[c]	Yes*[c]	—	Except freeways and interstate
Nevada	Yes	Yes	—	Yes	
New Hampshire	Yes	No	Yes	—	
New Jersey	Yes	Yes	Yes[a]	—	
New Mexico	Yes	Yes	Yes	Yes	
New York	—	—	—	—	
North Carolina	Yes[a]	Yes[a]	Yes*[a]	Yes	On streets ≤ 25 mph
North Dakota	—	—	—	—	
Ohio	Yes*[a]	Yes*[a]	Yes*[a]	—	Unless marked as exclusive pedestrian or bike path; On streets ≤ 55 mph
Oklahoma	Yes	Yes	Yes*[g]	—	On municipal streets

Table 2–2 (continued)

	Segway Permitted On:			Pedestrian Laws Apply	*Additional Comments
	Sidewalks	Bicycle Paths	Roads		
Oregon	Yes[a]	Yes[a]	Yes*[a]	Yes	On streets ≤ 35 mph
Pennsylvania	Yes*	No	Yes*	—	Unless prohibited by local jurisdiction; Not on a freeway
Rhode Island	Yes	Yes	Yes*	—	Unless bicycles are prohibited
South Carolina	Yes	No	Yes*	—	If sidewalk not available
South Dakota	Yes[a]	No	—	Yes	
Tennessee	Yes	Yes	Yes	—	
Texas	Yes	Yes	Yes*	—	On streets ≤ 30 mph and if sidewalk not available
Utah	Yes	No	Yes*	—	On streets ≤ 35 mph and < 4 lanes
Vermont	Yes	Yes	No	Yes	
Virginia	Yes*	No	Yes*	—	Unless prohibited by local jurisdiction; On streets ≤ 25 mph and if sidewalk not available
Washington	Yes[a]	Yes[a]	Yes*[h]	—	Not on controlled highways
West Virginia	Yes	No	Yes	Yes	
Wisconsin	Yes*[i]	No	Yes	No	Unless prohibited by local jurisdiction
Wyoming	—	—	—	—	

[a] EPAMD use may be restricted by local ordinance. San Francisco has banned EPAMD use on all sidewalks in the city and county as well as in public transit stations and vehicles. Municipalities in Alabama may prohibit EPAMDs on roads where the speed limit is greater than 25 mph.

[b] Only one person with a disability who has been issued a disability placard may use an EPAMD on a sidewalk or highway.

[c] EPAMDs are only allowed on highways to cross; EPAMDs may not be ridden along highways.

[d] EPAMDs are only allowed on highways with a speed limit of more than 30 mph to cross.

[e] EPAMDs may be required by local ordinance to use bicycle paths located adjacent to a roadway. If a rider is less that 16 years of age, and not accompanied by an adult, they must use a bikepath if located adjacent to a roadway.

[f] Local jurisdictions may allow EPAMDs on roads with speed limits higher the 35 mph.

[g] EPAMDs may be prohibited by municipality from operating on streets with higher than 25 mph.

[h] EPAMDs can locally be restricted to streets with speed limits up to 25 mph.

[i] EPAMDs cannot be operated on trails in state parks or forests unless specifically allowed by posted sign.

[j] In general no state prohibitions exist, but local regulations may exist.

Source: 22

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chapter three

Data Collection and Analysis

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Tindale-Oliver & Associates Inc.

3.1 Introduction

Since the introduction of mainframe crash databases in the 1970s, the ability of individual safety professionals and local agencies to capture, manage and analyze crash data has improved dramatically. Today, with the proliferation of in-vehicle laptop computers, desktop relational database management software, powerful geographic information systems (GIS) software and multiple specialized crash data analysis programs, an unprecedented level of access exists for those willing to take advantage of available tools.

This chapter highlights efficient methods of crash data collection, addresses important issues related to managing crash data and integrating crash data with other useful databases and demonstrates how a robust crash data management system can be used to optimize a safety professional's limited resources. Because crash data may pass through several agencies before they are available for analysis, this chapter also addresses necessary organizational issues to ensure a breakdown does not occur between data collection and analysis.

Besides describing methods to collect, organize and integrate crash data, this chapter demonstrates a top-down analytical approach that empowers safety professionals to proactively identify specific intersection safety problems rather than simply respond to citizen complaints. This approach includes multi-year trend analysis, temporal analysis (for example, seasonal, day of week, time of day), identification of driver behavior crash patterns and incorporation of land use and demographic data. This comprehensive approach identifies safety problems resulting from physical and operational characteristics of an intersection and enables the analyst to suggest law enforcement or educational priorities. It is hoped that an engineering analysis that informs enforcement decision-makers will help to solidify the relationship between safety professionals and the law enforcement community (whom the safety professional depends upon to provide accurate and complete crash data).

This chapter is limited in scope to an overview of an approach to the issues noted above. Beyond the other chapters of this report, the author of this chapter recommends several additional resources that deal with crash rate calculation, context-sensitive design issues and applicable countermeasures.[1–4]

3.2 Data Collection

The first link in the crash data collection chain is typically a law enforcement officer or police service technician. As illustrated in Figure 3–1, there are two basic data capture options: (1) completion of a hardcopy form and (2) data entry using an onboard laptop computer or personal digital assistant (PDA) device. Regardless of the method, the extent to which the circumstances and dynamics of the crash are accurately and completely recorded is critical to all crash data management and analysis processes to follow.

Proper hierarchy of the crash data within the database is illustrated in Figure 3–2. Sample crash data attributes are listed in Table 3–1.

3.2.1 Transcribe Hardcopy Report

The most basic means of capturing crash report data is to transcribe the hardcopy crash report into a database. Many first-generation crash data management systems employ this technique, which, if done consistently with due diligence, can yield useful results. As with any data entry process it is possible to establish look-up tables for data attributes, set required fields and build street name look-up tables to assist with the location process. Aside from the added effort and consequent potential for error associated with hardcopy data transcription, the greatest drawback of these systems is that they are characteristically mainframe-based and therefore do not offer adequate flexibility to the end user.

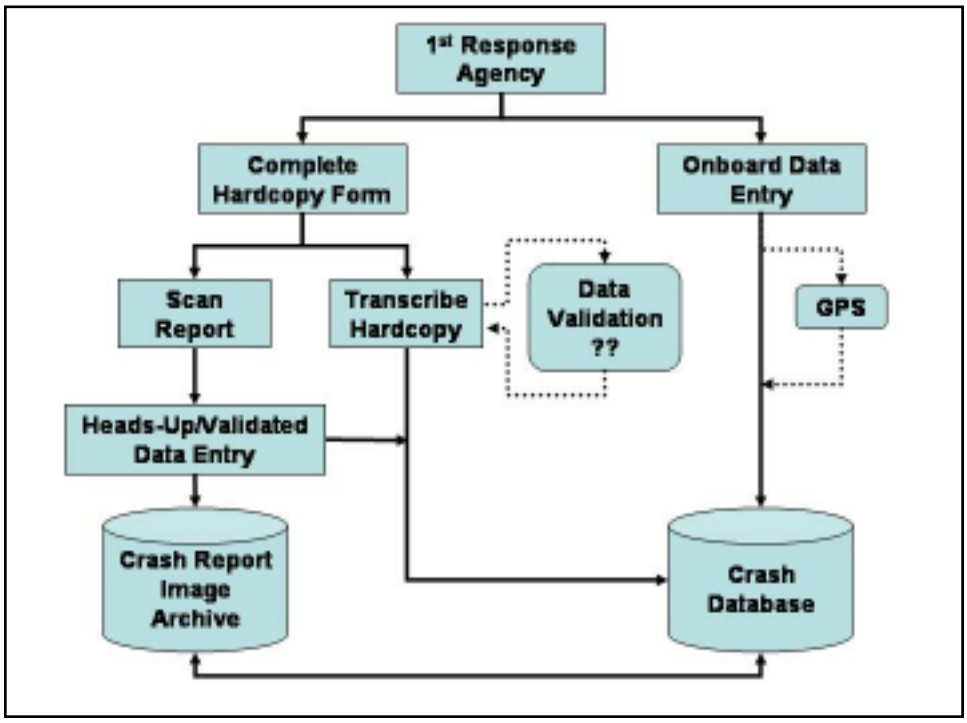

Figure 3–1: Data Collection Flow Chart
Source: Tindale-Oliver & Associates Inc.

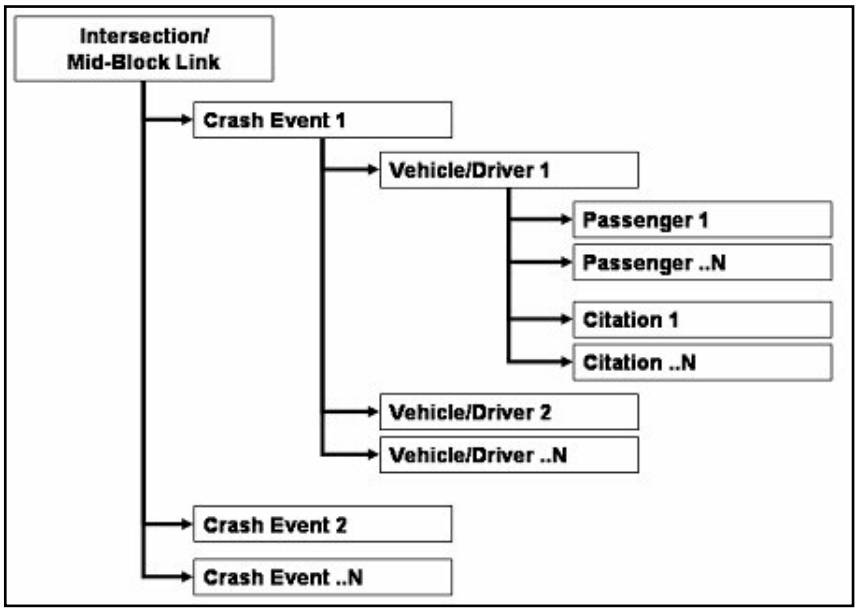

Figure 3–2: Crash Database Hierarchy
Source: Tindale-Oliver & Associates Inc.

Table 3–1: Sample Crash Data Attributes

	Event	
Basic	Date	*
	Time	*
	Location	*
	Site Location	#
Roadway	Number of Lanes	#
	Divided/Undivided	#
	Road Surface Type	#
	Trafficway Character	#
	Urban/Rural	#
	Traffic Control (s)	#
	Shoulder Type	#
Crash	Harmful Event (s)	*
	Rdwy Cont-Cause (s)	*
	Environ Cont-Cause (s)	*
	Lighting	*
	Weather	*
	Road Surface Cond.	*
	Property Damage	

	Vehicle	
Dynamic	Direction	*
	Movement	*
	Lane/Roadway Location	*
	Point of Impact	
	Estimated MPH	
	Posted Speed	
Vehicle Attributes	Vehicle Type	*
	Vehicle Use	
	Vehicle Year	
	Vehicle Make	
	Trailer/Type	
	Special Function (s)	
	Vehicle Defect (s)	
	Identification Number	
	Licence Plate Number	
	State of Registration	
	Owner's Residence	
	Hazardous Material	
	Placarded	
	Insurance	
	Vehicle Damage	

	Driver/Ped	
Driver Attributes	Age	*
	Gender	
	Ethnicity	
	Residence	
	Physical Defect	
	Contributing Cause (s)	*
	BAC Test Administered	
	BAC Results	
	Alchohol/Drug Use	*
	Driver Action	*
	Ped Action	*
	Driver License State	
	Driver License Type	
	Required Endorsements	
	Recommend Re-Exam	
	Injury Severity	*
	Ejection	
	Safety Device (s)	*

	Passenger
Passenger	Age
	Gender
	Ethnicity
	Residence
	Injury Severity
	Ejection
	Location in Vehicle
	Safety Device (s)

	Citation
	Violation Number
	Statute Number

* Critical Data Element
\# Derivable From GIS

Source: Tindale-Oliver & Associates Inc.

3.2.2 Field Data Entry

The most efficient method of crash data collection involves technology that enables the first respondent to enter crash attributes into a database at the scene of the accident. This may be accomplished via a laptop computer or a PDA device (see Figure 3–3). Advantages associated with field data entry devices are numerous and include the following:

- Field data entry eliminates intermediaries and propagation of error between the data collection and data management phases;
- Field data entry devices typically incorporate validated data entry features (look-up tables), thus adding greater uniformity and accuracy to data;
- The field data entry software may prohibit a first responder from omitting critical data elements;
- GIS crash location post-processing may be eliminated through easy interface with a global positioning system (GPS) device; and
- Field data entry reduces lag-time from incident to analysis (it keeps database as current as possible).

Figure 3–3: Field Data Entry System
Source: Tindale-Oliver & Associates Inc.

Although an increasing proportion of law enforcement officers are equipped with on-board computers, the expense and training necessary to fully implement field data entry for crash data is reflected in the extent to which law enforcement agencies continue to rely on hardcopy crash report instruments.

3.2.3 Validated Data Entry/Scanned Image Heads-Up Data Entry

Given the necessity of transcribing data from handwritten forms, several methods exist to expedite and add accuracy to the data entry process. At a minimum, the use of data entry user interfaces, which validate data entry against a list of acceptable values, should be adopted by all agencies. In addition to this basic accommodation, specialized data entry software is available that allows a user to enter data from a scanned image of the hardcopy crash report. Many agencies scan crash reports to avoid the logistics of storing several years of hardcopy files, but the usefulness of scanned reports in the data entry process itself is often overlooked. As shown in Figure 3–4, a scanned data entry report uses a template to navigate through the report image as each data entry field is processed. This type of data entry solution, though not as efficient as field data entry, may improve data entry speeds considerably while dramatically reducing data entry errors.

Regardless of the approach used for data entry, it is essential to provide for "hyperlink" retrieval of crash report images via GIS software, database systems and dedicated crash data management and analysis software. These are tremendous assets to the analyst once a specific location has been targeted for detailed study.

3.2.4 GIS Linkage

Crash statistics have historically been developed for specific locations using street name cross tabulation tables, internally consistent node systems and linear referencing schemes. However, the development of Windows-based GIS systems provides a unique ability to associate crash data with other data sets, such as land use, roadway infrastructure and demographic data.

There are three main methods by which individual crash events may be incorporated into a GIS system to ensure that sufficient information is captured in the data entry process to facilitate the use of this powerful

tool. Each of the three methods, as outlined below, compromises ease of use in the field with usability of data for analysis purposes.

1. XY coordinates from GPS device.
    a. Best suited to field data entry.
    b. May allow for exact position of vehicles in roadway if GPS device has offset capability and sufficient accuracy.
    c. Easy basic use with GIS, but requires post-processing to aggregate crashes to intersection or mid-block for statistical analysis.
2. Intersection, offset distance, direction from intersection.
    a. Commonly used because of ease of application in field in the absence of GPS capability.
    b. Requires extensive post-processing to integrate with GIS.
        i. Internally consistent street name look-up table.
        ii. Custom programming processing necessary to manage distance from intersection data.
3. Linear reference system route ID and milepost.
    a. Typically not used as a primary location capture technique except in rural areas or along limited access facilities.
    b. Provides easiest interface with asset/ infrastructure databases.
    c. Very difficult to accurately implement in the field.

In addition to the three methods noted above, the option exists for GPS to be complemented in the field by GIS software. This represents the best of both worlds in that it allows the responding agency to record the precise XY location of the crash and

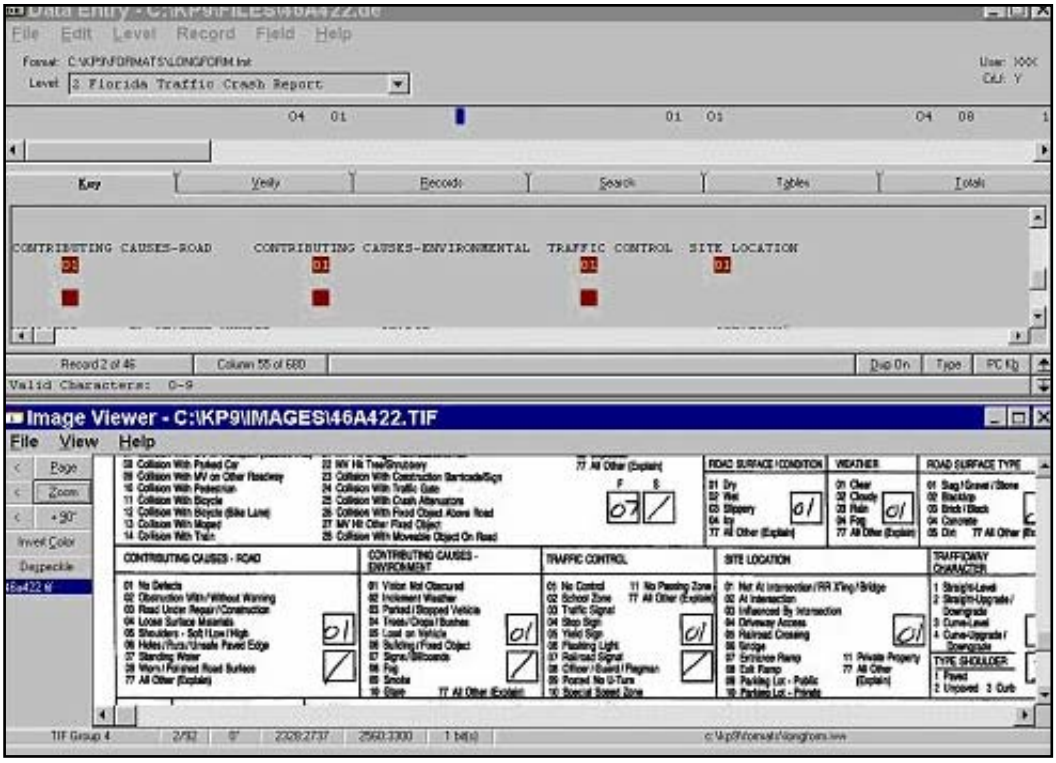

Figure 3–4: Heads-Up Data Entry User Interface
Source: Tindale-Oliver & Associates Inc.

immediately associate the crash with the appropriate intersection and/or mid-block records for aggregate data analysis purposes. Given the rarity of this capability, Table 3–2 describes the methods used to translate location data between the three modes described above.

Use of Table 3–2 can be illustrated by reviewing, for example, the transition from a linear reference crash data system to an intersection ID system. Starting in the "linear reference" row and proceeding to the "intersection ID" column, the table states that in a typical linear reference system, intersection features will also include route ID and milepost attributes. By designating a tolerance within which crashes are aggregated to an intersection or by locating crashes at the nearest intersection, a conversion can be made between the two systems.

The use of GIS for crash data analysis is reviewed more thoroughly in the data management and analysis sections of this chapter (3.3 and 3.4).

3.3 Data Management

Development and maintenance of a robust crash data management system enables a safety professional to use trends and data distributions from statewide or countywide data in conjunction with intersection-specific crash data to determine what is distinct about a subject intersection. Without delving into the particulars of relational database management, this chapter addresses two principal aspects of crash data management: (1) sharing state and federal data to develop a more complete, cost-effective crash database and (2) integrating crash data with other geographic/intersection-specific data sources such as roadway infrastructure, sign and pavement marking (asset), maintenance/work program, demographic and data regarding proximity to schools and special trip generators.

3.3.1 Use of Federal Data

Although most intersection safety analysis is performed at a local level, state and federal data can be used to supplement local data collection and

Table 3–2: GIS Methodology Translation Table

	XY Coordinate	Intersection ID	Linear Reference
XY Coordinate		Most GIS platforms include proximity analysis (buffer) tools that may be used to aggregate crashes with a given intersection or roadway segment.	Depending on the GIS software, a point feature generated from XY coordinates may be snapped to the nearest route and assigned a milepost. (ESRI ArcGIS 8.3 performs this function)
Intersection ID	Most GIS platforms can generate XY coordinates for point features. XY data for a specific intersection would apply to all crashes assigned to that intersection.		If a relationship table between intersection nodes and linear reference routes and milepost exists, it may be used to associate intersection crashes with the linear reference system. Otherwise, the milepost snap tool (above) may be used.
Linear Reference	Most GIS platforms can generate XY coordinates for point features, therefore XY attributes can be calculated for linear reference crash events. Some intermediate steps may be necessary depending on the GIS software platform.	Most linear reference systems will include route IDs and milepost for intersection features. Crashes within a specified tolerance of intersections may by assigned an intersection ID through a database query.	
Intersection Offset & Direction	Programs used to generate offset crash locations from intersection crash assignments typically yield XY coordinate crashes.	Given an intersection/node number, offset distance, and direction, crash data may be post-processed using GIS topology(1) to locate crashes along intersection approaches(2)	If a linear reference system is available, the crashes should first be assigned a route and milepost (above) and then the milepost should be adjusted according to the offset and direction data.

1. Topology is the relationship between line, point, and polygon features in a GIS
2. This approach is necessary to study mid-block crash statistics

Read Table From Left to Right and From Bottom to Top (Processes Are Not Reversible)

Page 1

Source: Tindale-Oliver & Associates Inc.

analysis efforts. At the federal level, the National Center for Statistics and Analysis (NCSA) of the National Highway Transportation Safety Administration (NHTSA) maintains the Fatality Analysis Reporting System (FARS). This data system was conceived, designed and developed by NCSA in 1975 to assist the traffic safety community in identifying traffic safety problems and evaluating both motor vehicle safety standards and highway safety initiatives. To be included in FARS, a crash must involve a motor vehicle traveling on a traffic way customarily open to the public and result in the death of a person (either an occupant of a vehicle or a non-motorist) within 30 days of the crash. Each case has more than 100 coded data elements that characterize the crash, vehicles and people involved. All data elements are reported on four forms and incorporated into three relational database tables:

- The accident form compiles information such as the time and location of the crash, the first harmful event, whether it was a hit-and-run crash or if a school bus was involved and the number of vehicles and people involved.
- The vehicle form and driver form compile data on each crash-involved vehicle and driver. Data include the vehicle type, initial and principal impact points, most harmful event and drivers' license status.
- The person form contains data on each person involved in the crash, including age, gender, role in the crash (for example, driver, passenger, non-motorist), injury severity and restraint use.

FARS also includes alcohol files that contain driver and non-occupant BAC (blood alcohol content) estimates, as well as overall crash alcohol estimates. These are used to supplement the data files when no alcohol information is otherwise available (www-nrd.nhtsa.dot.gov/departments/nrd-30/ncsa/fars.html). In addition to FARS, the Federal Motor Carrier Safety Administration (FMCSA) maintains the Motor Carrier Management Information System (MCMIS) that tracks fatal and non-fatal crashes of large trucks and busses (ai.volpe.dot.gov/CrashProfile/CrashProfileMainNew.asp). FARS and MCMIS are limited in that they only record data for fatal and freight-related incidents.

3.3.2 Use of State Data

At the state level, either the state transportation, highway safety, or motor vehicle agency is responsible for soliciting and transcribing crash reports from local law enforcement agencies. Although a route ID and milepost is typically assigned to crashes on state roads, it is not common for states to provide specific location data for off-system crashes.

Many states maintain crash databases for varying subsets of the total crash population. Typically, these data are used to identify crash patterns and trends by jurisdiction to inform state safety engineering and law enforcement priorities. Although state crash data often do not include the location information necessary to identify and improve specific intersections, use of state data in a hybrid data collection scheme, as shown in Figure 3–5, may significantly reduce data entry effort at the local level and allow greater investment in analysis activities.

In this data capture scenario, hardcopy (or digital) crash reports are “intercepted” prior to submittal to the responsible state agency and are entered into an extremely basic inventory using only the crash reports’ case ID number, incident date and location data. When annual data are published by the state, the local agency may then link its inventory to the complete state database to develop comprehensive, location-specific data with minimal data-entry effort. If the state agency archives scanned crash report images, these may be retrieved as needed from the state’s server. If no images are archived at the state

level, it is still possible to include report scanning in the "intercept" process.

Although this model introduces delay and an element of dependency, the sheer bulk of statewide data entry allows for sophisticated quality control procedures that may not be feasible to implement at the local agency level. Of even greater benefit is the resulting compatibility of local data and state data, allowing safety professionals to more easily compare local trends with statewide data.

One successful example of a state-implemented data collection and management model is the national model developed by the state of Iowa in conjunction with FHWA. This model utilizes the Traffic and Criminal Software (TraCS) system to link in-car data collection and location with a statewide database in a manner that requires minimal user intervention.*

3.3.3 Integrating Data

Although essential for intersection safety analysis, crash data is only one of several elements in the safety professional's geographical database. Although the ultimate resolution of intersection safety problems typically necessitates field work, linkage of the following data through a GIS/MIS platform allows summary reviews to be performed with greater efficiency, thereby allowing more time to be spent on particularly complex or otherwise pernicious crash problems:

- **Roadway infrastructure data** such as number of lanes, posted speed, pavement width, pavement condition, presence of turning lanes, length of storage lanes and other intersection geometric data can be used to explain crash patterns.
- **Sign and pavement marking (asset) data** are particularly useful when they indicate the absence of critical signage and/or markings that may contribute to crashes at a particular intersection.

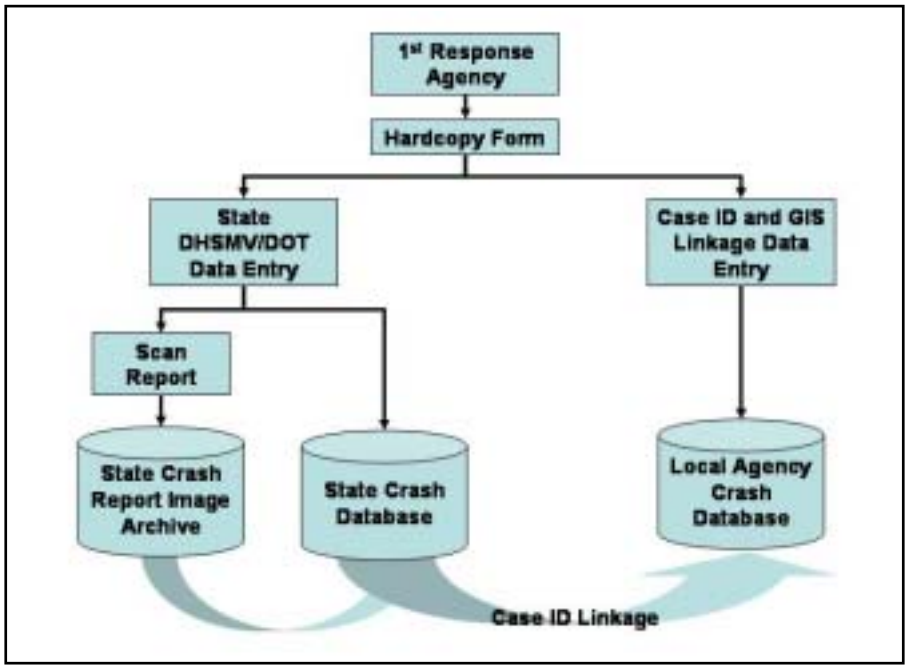

Figure 3–5: State Data-Sharing Data Collection Flow Chart
Source: Tindale-Oliver & Associates Inc.

* www.dot.state.ia.us/natmodel/index.htm

- **Traffic operations data** are necessary to establish crash rates and can be extremely useful in diagnosing crash problems. Crash rates are important because they normalize crash frequency for volume and can be helpful in identifying locations that are unusually dangerous and therefore merit investigation. Injury (or injury severity) rates may also be used to identify dangerous locations. In addition, specific types of crash rates can be compared to norms for similar intersection configurations. The most basic traffic operations data include entering volume, but may be extended to entering and exiting volume by approach, turning movement count data, intersection level of service (congestion), approach speed, percent trucks, bicycle and pedestrian volume and queue lengths. If volume data are maintained for hourly intervals, it may be correlated with time of day crash statistics to determine whether peak periods for crashes are real or incidental.
- **Traffic control data** allow several types of crashes to be diagnosed efficiently. For example, angle collisions (and sometimes rear-end collisions) may be the product of an inappropriately timed clearance interval. Left-turn collision patterns may suggest the need to convert a permissive left-turn phase to a protected or protected/permissive phase.
- **Maintenance/work program data** may enable a safety professional to determine whether a problematic intersection can be improved as part of scheduled capacity improvements or maintenance activities. Linkage of work program to crash data may result in cooperation between safety staff and roadway capacity and design staff for the benefit of both departments.
- **Demographic data and land use data** are useful as a surrogate for the population traveling through an intersection. For example, population age may be correlated to driver age data from crash records to determine if abnormal crash data trends are apparent. Land use data may also serve as a proxy for bicycle and pedestrian volume data and can be used to explain unusual temporal peaks caused by commercial and entertainment land uses or special generators, such as arenas and schools.
- **Aerial imagery** can complement or substitute for infrastructure data, provided that the vintage of the aerial is recent and known to the analyst. Although aerial imagery cannot be used in database filters to identify specific relationships between crash patterns and infrastructure, it provides an excellent means of reviewing intersection geometrics if the resolution is 1 ft. or better.
- **Street-level photo or video logs** are tools that can help the engineer develop an understanding of the issues related to a crash problem at a particular intersection. Street-level imagery can help diagnose sight obstruction problems and, like aerial imagery, can complement or substitute for infrastructure and asset data.

The wealth of database and imagery resources available varies greatly by jurisdiction. Typically, infrastructure and asset data will be stored by linear reference schema, while traffic operations and control information are often assigned a cross street name pair. Land use data and demographic data are usually maintained within the jurisdiction's GIS platform and are relatively easy to associate after crash events have been effectively located. Aerial imagery is highly compatible with GIS systems, assuming reference data are provided for each image. Street-level imagery may be hyperlinked through either a GIS or database management system such as Microsoft Access (or Excel).

It is critical that database linking fields and translation tables are complemented by well-established

standard operating procedures (SOP) and memoranda of understanding (MOU). For most jurisdictions, it is unlikely that the various data mentioned above will be maintained within one organizational unit. Indeed, some data may be managed by an entirely different agency. In the example shown in Table 3–3, there is a concentration of data management by the public works traffic services division. But the establishment of peer-level links with other units, particularly the sheriff's office where an MOU establishes a responsibility-sharing relationship, is critical to successful maintenance of the geographic crash analysis database.

3.4 Data Analysis

In the course of analyzing crash data, a safety professional might for example, encounter three study areas that respectively exhibit a large number of crashes involving elderly drivers, a high proportion of run-off-the-road and head-on collisions and an extremely high percentage of rear-end crashes with injury. Although these clues are interesting, without knowledge of the surrounding area, they are essentially useless. An unusually old driver age distribution may be unusual in some areas, but is common in Florida. A high proportion of head-on and run-off-the road crashes may be unusual in an urban area but may be typical for a rural county. And an exceptional number of rear-end crashes at an intersection may be standard for a high-speed corridor with long cycle length and correspondingly long queues. Without this global perspective, seemingly profound crash data attributes for a particular location may obscure the real issues and prevent an analyst from determining what is truly unique about a given location.

As Figure 3–6 suggests, with the shift in focus from statewide/national crash trends to intersection-specific data attributes, the safety professional must use different tools to manage the data. At a state/county comparative analysis level, database management or statistical analysis software such as Access, Excel, FoxPro, or SPSS may be appropriate to establish trends and proportions. When reviewing regional or corridor level data sets, general database management software may still be useful to identify relationships, but introduction of GIS may aid in identifying spatial relationships and patterns. At the intersection (or segment) level of analysis, specialized crash data diagramming and analysis software may be employed to study crash patterns and types. Finally,

Table 3–3: Example of Data Sharing Across Organizational Units and Agencies

Data	Source/Maintained By
Data Collection/Data Entry	Sheriff's Office
Infrastructure and Geometrics	Public Works—Traffic Services Division
Signs, Markings, Assets	Public Works—Traffic Services Division
Traffic Volume (Annual Counts)	Planning and Growth Management
Traffic Volume (Study-Specific)	Public Works—Traffic Services Division
Traffic Control	Public Works—Traffic Services Division
Demographic	US Census Department
Land Use	Planning and Growth Management
Aerial Imagery	Survey and Mapping/Property Appraiser
Photo Log	Public Works—Traffic Services Division
GIS Data	Information Services Department

Source: Tindale-Oliver & Associates Inc.

the use of scanned image archives may be relied on after more macroscopic analysis has confirmed the location is worthy of detailed study.

The following sections present case studies in the use of a methodology that compares trends between small sample sets of crash data to help determine whether a crash problem at a particular intersection exhibits any distinguishing characteristics which point to an engineering, enforcement, or education solution.

3.4.1 Statistically Significant Crash Rate Categories

State and federal agencies have undertaken the complex task of establishing crash rates by roadway and intersection characteristics. If roadways are classified based on only three variables (number of lanes, area type and median type), between 30 and 40 separate categories emerge depending on the specificity of each variable. If similar criteria are applied to an intersection, the number of permutations becomes challenging, especially considering the necessary addition of traffic control variables. Data structures capable of managing the relationships necessary to establish complex intersection crash rate categories have been developed by numerous agencies. However, it is not uncommon for multiple categories to be under-populated to the extent that no statistically significant rate may be established. Due to the wealth of research published on this subject and the limited context of this chapter, a discussion of crash data analysis using statistically significant crash rates is not presented here. Rather, the remainder of this chapter focuses on the use of simple trend analysis, data filters and two-dimensional cross-tabulations to identify problem areas and suggest solutions.

3.4.2 Comparative Analysis

At the federal level, the General Estimate System (GES), a component of National Automotive Sampling System (NASS) maintained by NHTSA, obtains data from a nationally representative probability sample selected from the estimated 6.4 million police-reported crashes that occur annually. These crashes include those that result in a fatality or injury and those that involve major property damage. By

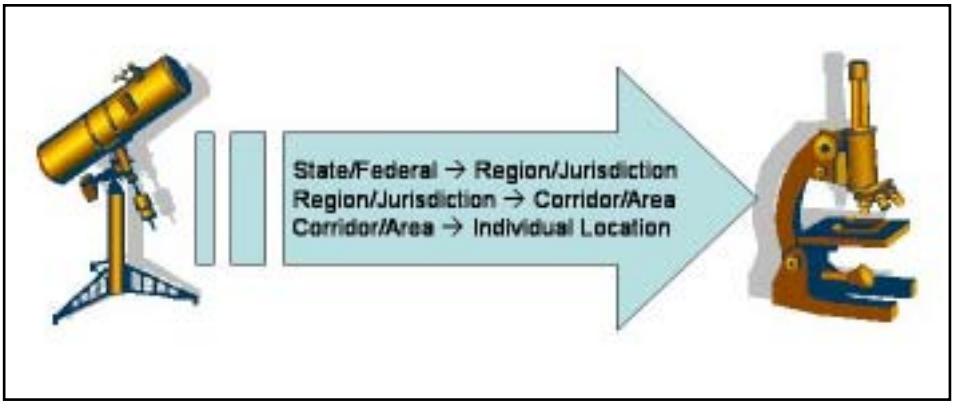

Figure 3–6: Analytical Approach
Source: Tindale-Oliver & Associates Inc.

restricting attention to police-reported crashes, GES is used to identify highway safety problem areas, provide a basis for regulatory and consumer information initiatives and facilitate cost and benefit analyses of highway safety initiatives.*

In the same way, state-level data may be compared to county or corridor data to establish which trends are significant and which are incidental. Establishing the correct context for crash data analysis is very important. For example, assume an analyst wants to determine which roadways are most in need of drainage improvements. One approach is to compare local data to national data to determine where a disproportionate number of crashes involve wet roadway surface conditions. However, this approach will not yield meaningful results in states with significantly dryer or wetter climates than the norm (for example, Arizona). A comparison to state or county/regional data may indicate roads with disproportionately high numbers of precipitation-related crashes.

With the aid of a robust database, the experienced safety professional may take the lead and develop a priority improvement list that combines traditional engineering knowledge with state of the art information. Rather than focusing strictly on intersections with high crash frequencies or injury frequencies, the safety professional may add color to the prioritization process through selective data permutations. For example, the database could be used to identify all intersections with both high left-turn crash rates and permissive left-turn signal phasing. Or, the database could identify all functionally classified roadway intersections that are located within one-fourth of a mile of an elementary school and are not equipped with sidewalks and pedestrian signals. While the local safety professional may not have a sufficiently large sample size to declare with certainty what rates are "abnormally high," this should not prevent attempts to use data to this end.

3.4.3 Temporal Analysis

Development of consistent multi-year crash databases enables the safety professional to analyze the trend of crashes during an extended period. While the two or three most recent years are often considered to be a sufficient database period, crash histories during a 5- to 10-year period are helpful in identifying some underlying causal factors.

Case Study A: Figure 3–7 shows a crash frequency history for a sample non-signalized intersection along a minor arterial with a dramatic change in crash frequency during a 5-year period.

A review of the figure indicates a trend increase from four crashes to 16 crashes annually in the span of 3 years. Although this might not be considered an especially high number of crashes overall, the trend is alarming. Potential causes for this increase could be proportionately heightened traffic volumes or changes to the physical environment at the intersection. These hypotheses can be tested quickly and efficiently if the investigator has ready access to work program and traffic volume data.

In the case of the sample intersection documented in Figure 3–7, main street traffic volumes have remained stable during the analysis period and therefore do not explain the crash trend. Likewise, there have been no changes to the intersection operation nor has there been adjacent development of a significant nature. Although no changes have been made to the intersection itself, review of work program history and aerial imagery reveals a neighborhood traffic calming initiative was recently implemented in the neighborhood served by the intersection. Speed tables have been installed throughout the neighborhood. The subject intersection is located along one of the few routes through the neighborhood that does not have a speed table. As a result, traffic on the minor road approach to the intersection has likely increased. In addition, review of the site indicates that

* www.transtats.bts.gov/DatabaseInfo.asp?DB_ID=600&Link=0

an adjacent commercial driveway may constitute a sight obstruction if occupied by a vehicle.

Case Study B: As well as reviewing crash trends during the course of several years, it is often helpful to view data seasonally or monthly. Figure 3–8 shows sample crash frequency by month of year for a sample site in Florida. There is a clear spike in crash frequency during August. In Florida, peak traffic volumes typically occur during the December through March tourist season. Therefore, a peak in crashes during August is unexpected.

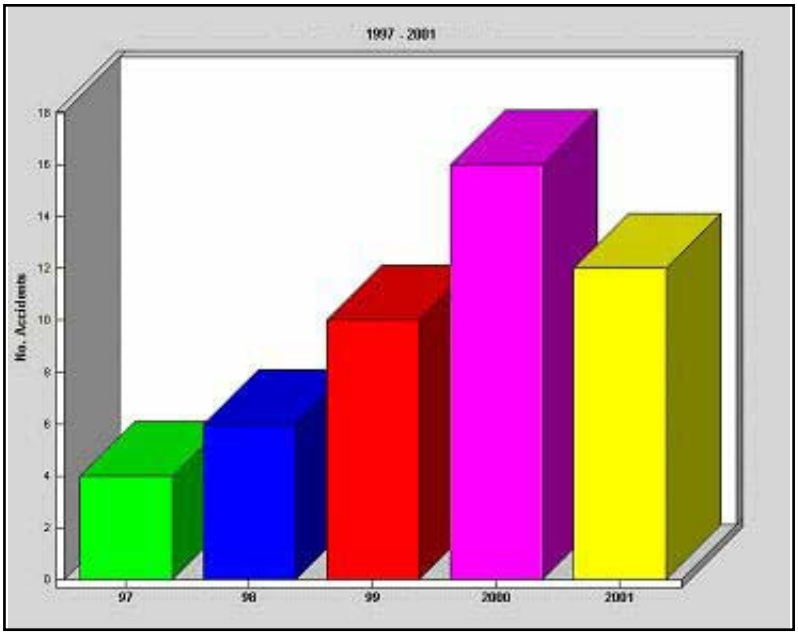

Figure 3–7: Annual Trend in Crashes at Study Intersection
Source: Tindale-Oliver & Associates Inc.

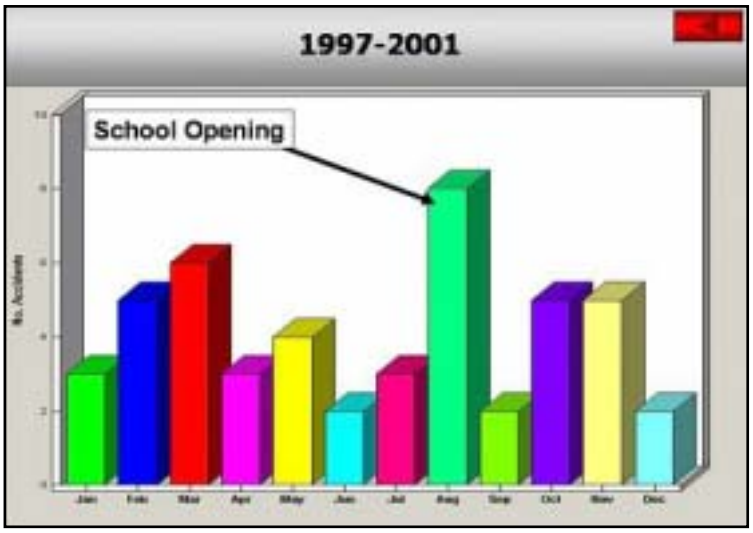

Figure 3–8: Monthly Trend in Crashes at Study Intersection
Source: Tindale-Oliver & Associates Inc.

In this case study, land use data is the key data element necessary to explain the abnormal crash problem. Using GIS, it is apparent that a major elementary school is situated a few hundred feet from the study intersection. The school opens in August and generates an annual surge in traffic during the first month of its operation.

For the same location, 5 years of data are used to generate a day-of-week distribution. Figure 3–9 shows a clear peak crash frequency on Fridays. Although traffic count data should be used to confirm whether the weekly crash pattern is tied to traffic volume, the prevalence of commercial land uses near the intersection suggests increased Friday evening traffic as a reasonable hypothesis for a contributor to the safety problem.

Further review of this location using time-of-day analysis confirms the crashes peak between 3:00 and 4:00 p.m. and at approximately 7:00 p.m. Figure 3–10 further strengthens the hypothesis that school and commercial trip generation explain the abnormalities in the intersection's temporal crash data distributions. Additionally, should this intersection exhibit other abnormal factors deeming it worthy of detailed study, the temporal distribution data suggest the appropriate times to perform field reviews.

After using all of the available resources, field review of the study intersection suggests that, although the main street traffic volume has not changed significantly, side street entering volumes have increased to the extent that a traffic signal may be warranted to abate the angle crash problem shown in Figure 3–11.

3.4.4 Crash Pattern/Cluster Analysis:

Most safety professionals are familiar with the analysis of crash clusters using collision diagrams (such as the example shown in Figure 3–11). After crashes are filtered for different crash data attributes, more specific crash patterns can be observed.

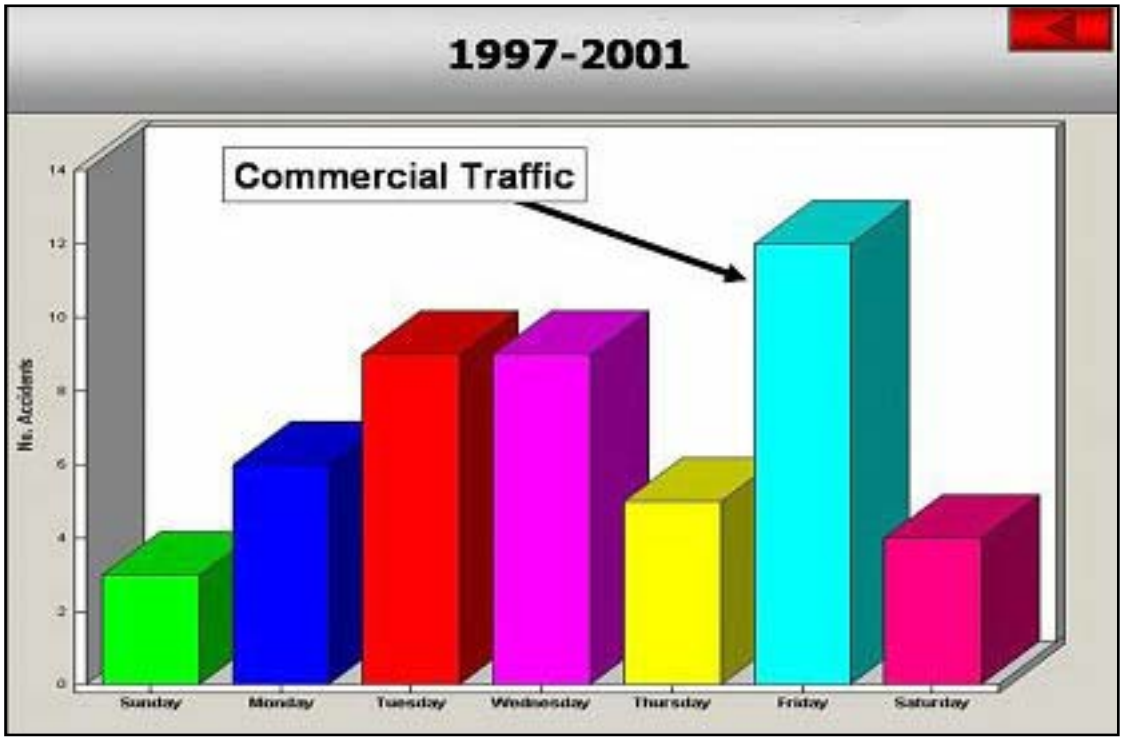

Figure 3–9: Day of Week Graph of Crashes at Study Intersection
Source: Tindale-Oliver & Associates Inc.

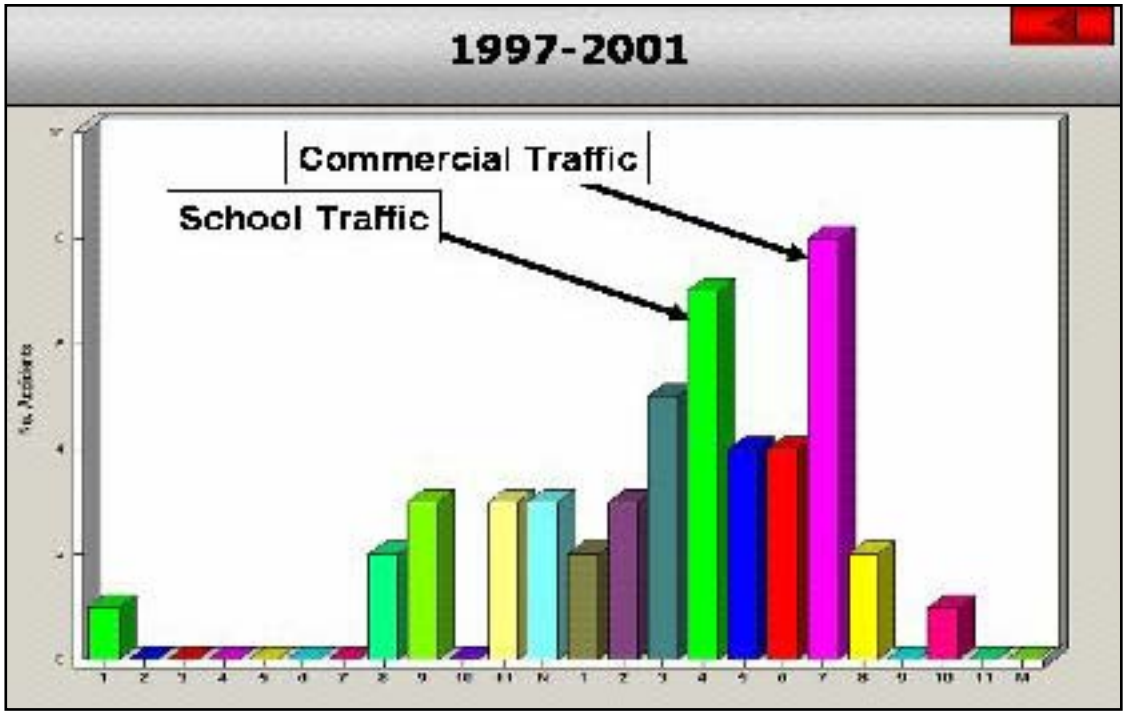

Figure 3–10: Time of Day Graph of Crashes at Study Intersection
Source: Tindale-Oliver & Associates Inc.

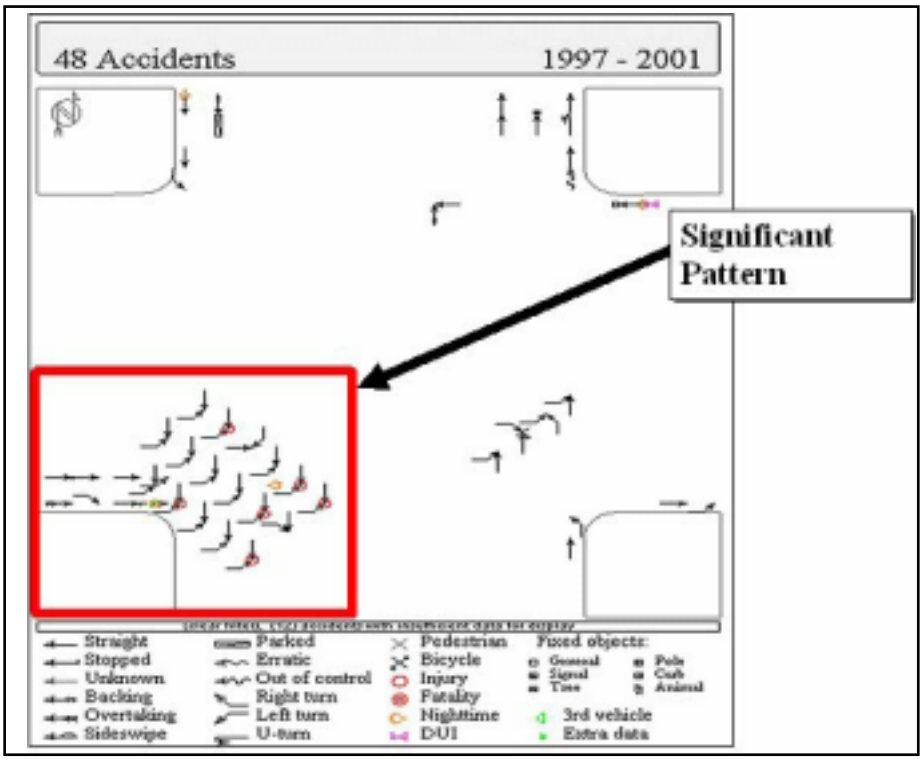

Figure 3–11: Computer-Generated Collision Diagram for Study Intersection
Source: Tindale-Oliver & Associates Inc.

Case Study C: Table 3–4 presents a cross-tabulation that relates weather condition and first harmful event for crashes at a sample problem intersection. Table 3–5 presents comparative percentages derived from the Table 3–4 data and a countywide database. The subject intersection has three times the number of wet weather collisions than is typical for the county (30 percent versus 9 percent). Although the overall proportions of rear-end collisions are similar (34 percent at the intersection versus 37 percent countywide), the difference in the proportion of wet weather rear-end collisions is dramatic (17 percent at the intersection versus 4 percent countywide).

Case Study D: Table 3–6 presents an analysis of the distribution of crashes by driver age and rear-end first harmful event for a study corridor and intersection. Attention is directed to the fact that the sample corridor exhibits a much higher proportion of rear-end collisions than the surrounding five county state DOT district (48 percent versus 32 percent). Further, a sample intersection along this corridor demonstrates a 66 percent rear-end collision rate.

From Table 3–6, it is also apparent that twice as many crashes along the study corridor involve at-fault elderly drivers than in the DOT district as a whole (24

Table 3–4: First Harmful Event/Weather Cross-Tabulation for Subject Intersection

	Intersection (%)	Countywide (%)
Rain Crashes	30	9
Rear-End Crashes	34	37
Rear-End/ Rain Crashes	17	4

Source: Tindale-Oliver & Associates Inc.

Table 3–5: Comparison Between Subject Intersection and Countywide Crash Data

First Harmful Event	Clear	Cloudy	Rain
All Other	8	2	4
Angle	10	2	2
Head On	6	0	1
Rear End	7	2	9

Source: Tindale-Oliver & Associates Inc.

Table 3–6: Analysis of Sample Distribution of Crashes

	DOT District (%)	Corridor (%)	Intersection (%)
Percent of All Crashes with Rear-End First Harmful Event	32	48	66
Percent of Age 65+ Crashes with Rear-End First Harmful Event	22	37	36
Percent of All Crashes with At-Fault Driver Age 65+	12	24	14

Source: Tindale-Oliver & Associates Inc.

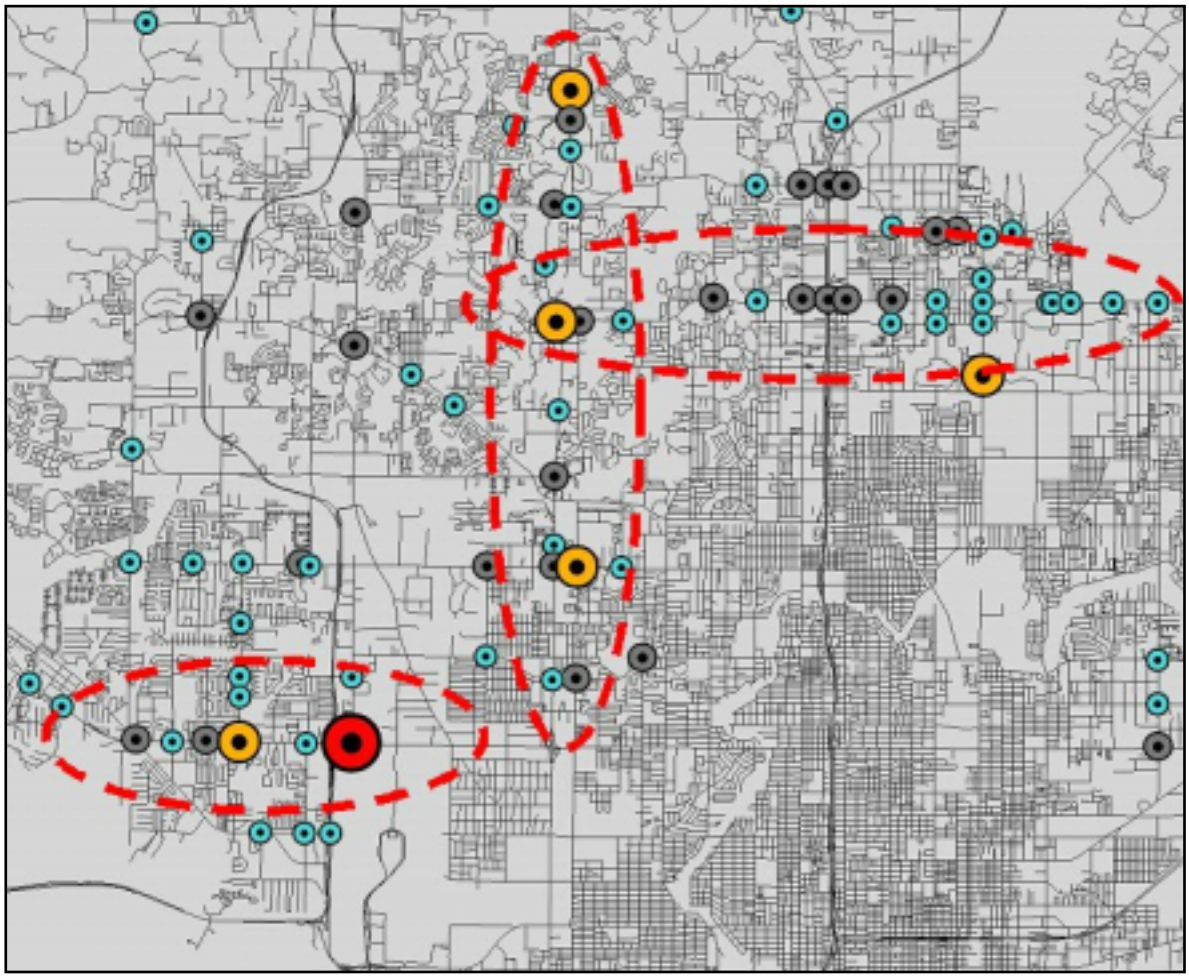

Figure 3–12: Red-Light Running Crash Map
Source: Tindale-Oliver & Associates Inc.

percent versus 12 percent). An analyst might surmise that age-sensitive design measures could improve safety along the subject corridor and consequently improve intersection safety. However, the data also show that elderly driver collisions are less likely to involve rear-end first harmful events (22 percent versus 32 percent at the district level and 37 percent versus 48 percent at the corridor level). Further scrutiny (of data not shown here) indicates a key difference between the subject intersection and the corridor. Although the total proportion of rear-end collisions has increased dramatically, the proportion of rear-end collisions among the elderly has not increased. As such, elderly drivers account for only 14 percent of the total crashes at the intersection and it is unlikely that safety at this intersection will be directly improved by corridor-wide implementation of design measures that target elderly drivers.

Case Study E: By filtering for other data elements in crash reports and linked data discussed in the data management section of this chapter, the analyst can isolate and better understand other human factors. Figure 3–12 shows crashes linked to citation data, specifically red-light running, in a sample urban area. These data are useful to the safety professional as it may suggest alteration in signal operations along these corridors. It also may be used by law enforcement to allocate traffic enforcement resources more efficiently.

A thorough review of red-light running crashes within the study area identified two trends. First, red-light running crash problems tended to occur at intersections with congested left-turn issues, long cycle lengths and cycle failures. Second, one-way pairs with good signal progression and high travel speeds seemed to elicit red-light running behavior. Although a study of statistical significance was not performed to verify or reject these hypothesis, local traffic safety professionals, through the integration of crash, asset, traffic operations and other data, are now better equipped with the means to perform such an analysis.

3.5 Conclusion

This chapter addressed three aspects of crash data and analysis for intersection safety improvement: 1) data collection, 2) data management and 3) data analysis. Though necessarily written from an overview perspective, it demonstrates how the availability of comprehensive, geographically discrete crash data, in conjunction with related databases, empowers safety professionals to identify causal factors more easily and efficiently and to use the most complete available data to proactively set intersection safety improvement priorities.

The data collection section of this chapter illustrates the importance of establishing a solid institutional relationship between local safety professionals, law enforcement and state crash data management agencies to the mutual benefit of all parties. Further, this section demonstrates several techniques to improve data entry accuracy and efficiency and stresses the importance of developing well-planned and up-to-date linkages with the relevant jurisdiction's GIS system.

The data management section builds on the foundation of solid data collection processes and demonstrates how, through the use of relational database management software and contemporary GIS platforms, many useful data sources can be incorporated in an agency's crash data management system. These sources, which include traffic operations data, signal control plans, work program histories and priorities, land use and special generator data, and aerial and street-level imagery, can be used to enhance an analyst's understanding of a problem intersection—in some cases beyond what could be gleaned from field review.

This chapter concludes with a presentation of analysis techniques made possible by implementing the data collection and management practices discussed herein. While respecting the benefits of statistically significant crash rate category definitions and intersection improvement benefit-cost ratios, this

section shows how comparative analysis can be performed in the absence of statistical validity using more basic concepts of ratio and proportion combined with intelligent selection of sample/population data sets. The following process may be used for identifying and reviewing problem intersections:

1. Filter data as appropriate to normalize the comparison. Some basic filters, which may be used without developing complex crash rate categories include:
    a. signalized/unsignalized
    b. urban/rural
    c. functional classification
2. Compare the following intersection data with state/federal, county/jurisdiction and corridor/study area data:
    a. first harmful event
    b. driver contributing cause
    c. roadway contributing cause
    d. environment contributing cause
    e. lighting condition
    f. crash rate
    g. driver age
    h. injury severity
    i. bicycle and pedestrian crashes
3. Review temporal trends with respect to seasonal volumes, hourly traffic counts and adjacent land uses (corridor/area temporal trends may be used if traffic volume data is not available) such as:
    a. yearly frequency (3-year minimum)
    b. month-of-year
    c. day-of-week
    d. time-of-day
4. Review crash patterns with respect to intersection attributes and work program data such as those listed below. Given comprehensive traffic count and infrastructure data, elements of this process may be automated:
    a. traffic control type/parameters
        i. two-way vs. four-way stop
        ii. signal phasing
        iii. signal timing
        iv. pedestrian signals
        v. posted speed limit or 85th percentile speed
    b. traffic operations
        i. entering volume (by approach), classified by vehicle type
        ii. bicycle and pedestrian volumes
        iii. queue lengths
        iv. intersection level of service
    c. intersection design
        i. approach lane configuration
        ii. storage lane length
        iii. crosswalks/bike lanes/refuge areas
        iv. access management issues
        v. lighting
    d. work program
        i. are temporal trends in the crash data consistent with maintenance of traffic issues related to roadway construction?
        ii. are committed improvements applicable to the crash pattern?
5. Perform field review

Willingness to review crash data at a macroscopic level is important because it provides the safety professional with the ability to set priorities, as well as solve pre-defined problems. This section also demonstrates how the combination of temporal patterns, adjacent land uses, driver attributes and driver behavior may be reviewed in conjunction with traditional crash patterns to isolate complex causal factors at the intersection level. The examples provided herein are by no means meant as an exhaustive exposition on the subject. Rather, they are intended to wet the appetite of a data-hungry safety professional who must deal with intersection safety on a daily basis.

The analytical approach conveyed in this chapter demonstrates how a solid history of raw crash data, when combined with other data assets, can be used to dissect an intersection crash problem and make sense of seemingly spurious relationships. Without conducting a turning-movement study or reviewing detailed crash report narratives, sufficient evidence can be assembled to "indict" the subject intersection. Having undertaken a comprehensive screening and data analysis process, the probability that field review and a signal warrant study will yield definitive results has been increased and a better use of the agency's assets has been achieved.

In conclusion, a good systematic approach to data collection, management and analysis for intersection safety improvement does not necessarily require complex algorithms or even many of the data elements described here. Rather than suggesting that safety professionals wait for the availability of a perfect, one-stop crash data management system, this chapter attempts to demonstrate the substantial decision-making enhancements that can be accomplished with the tools available today. As more agencies implement comprehensive crash data management systems, their ability to optimize data management efforts will increase and pre-packaged systems will likely become available. Until then, it is incumbent upon each safety professional to seize the best available tools and dive in.

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chapter four

Pedestrian and Bicyclist Safety at Intersections

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Tim J. Gates
and Janet M. Barlow

University of Wisconsin—Madison; Accessible Design for the Blind (Barlow)

This chapter presents information pertaining to design and operation treatments that specifically address the safety needs of non-motorized users at intersections. Particular focus is placed on pedestrians and bicyclists. Some mention is made of transit-related issues. Treatments that specifically pertain to motorists are covered in Chapters 5 through 8.

Numerous photographs are included in this chapter to illustrate concepts, not design details. Application of these concepts requires adherence to all federal and local design standards.

4.1 Design Elements Related to Pedestrians

Design and safety guidelines for pedestrians are contained in numerous publications.* This section summarizes key elements of intersection design and presents successful applications that directly affect the safety and mobility of pedestrians. For detailed guidance, the reader should review the references provided at the end of this chapter.

* Pedestrian characteristics and design criteria are addressed in the AASHTO *Green Book*,[9] the *Highway Capacity Manual*, [17] or the American Institute of Architects (AIA) *Graphic Standards*.[29] A recent publication by AASHTO titled *Guide for the Development of Pedestrian Facilities* provides a comprehensive overview of design and safety guidelines for pedestrians.[10] Other important references on the topic of pedestrian facility design are *Design and Safety of Pedestrian Facilities*,[11] the *Pedestrian Facilities Users Guide: Providing Safety and Mobility*,[30] *Designing Sidewalks and Trails for Access*[12] and *Alternative Treatments for At-Grade Pedestrian Crossings*.[31] The U.S. Access Board (www.access-board.gov) is also a source for pertinent publications including *Accessible Public Rights-of-Way Design Guide* and *ADA Accessibility Guidelines*.[13,14]

4.1.1 Crosswalks

4.1.1.1 Marked Versus Unmarked Crosswalks

Marked crosswalks should be provided at all intersections where there is a substantial conflict between motor vehicle and pedestrian movements.[1] Because conflicts are not necessarily a direct function of traffic volumes, this guidance applies to roadways of any functional classification and to all types of intersections (signalized, stop-controlled and uncontrolled).

Marked crosswalks serve three primary functions:

1. Inform the pedestrian of the preferred crossing location;
2. Alert motorists of pedestrian crossing point locations; and
3. Establish a legal crosswalk at that particular location.[1,2]

The connection of sidewalks from opposite sides of an intersection (or, in the absence of a sidewalk on one side, the lateral extension of the sidewalk across the intersection perpendicular to the centerline) represents a crosswalk regardless of whether it is marked or unmarked.[1,4] Unmarked crosswalks are typically reserved for intersections not controlled by traffic signals or stop signs. However, the fact that a crossing is not marked should not minimize the importance of user safety. Potential methods of improving user safety at intersections with unmarked crossings include raised medians, pedestrian refuge islands, curb extensions to shorten crossing distance and raised crossings.[3] If sidewalks are present, curb ramps are required.

4.1.1.2 Uncontrolled or Midblock Intersections

Data from two studies indicate that pedestrian crash frequency at marked crosswalks at uncontrolled intersections is directly related to motor vehicle traffic volume and is relatively independent of pedestrian traffic volume.

- Pedestrian crashes at such crosswalks in California were found to be rare at locations with motor vehicle traffic of less than 2,700 ADT (average daily traffic), with most pedestrian crashes occurring at locations with greater than 6,000 ADT.[5]
- Pedestrian safety at marked and unmarked crossings at uncontrolled or mid-block intersections was found to be statistically similar on two-lane or multi-lane roads with ADTs of 12,000 or less.[3] However, marked crossings were found to have higher pedestrian crash rates versus unmarked crossings on multilane roads with ADTs of greater than 12,000.

These results suggest that marked crosswalks at uncontrolled intersections on high volume multilane roadways without other pedestrian enhancements may create a false sense of security for crossing pedestrians. If installed, they are best used in combination with other treatments (for example, curb extensions, raised crossing islands, contrasting pavement colors, in-pavement flashers, traffic signals).[3]

4.1.1.3 School Zones

School zones present a particularly critical situation for pedestrian safety. Children are typically more unpredictable than adults at pedestrian crossings, increasing the need for a high level of driver awareness and safe crossing locations.

Marked crosswalks should be used at school zone crossing areas regardless of the level of traffic control. Supplemental pedestrian safety treatments, such as adult crossing guards, should also be used where necessary. Fluorescent yellow-green school signing is recommended to better alert drivers of a school zone. In California, all crosswalk markings that coincide with a "Safe Route to School" are colored yellow. In this regard, California is unique in the United States for its use of colored crosswalks. This special treatment conforms to the *California Traffic Manual*,

California's own adopted *Manual of Uniform Traffic Control Devices* (MUTCD).[6]

4.1.1.4 Crosswalk Markings

The MUTCD states that crosswalk markings, if used, shall consist of solid white lines between 6 and 24 in. in width.[1] Since the MUTCD does not specify preferred patterns for crosswalk markings, many types of crosswalk marking patterns are in use. The type of crosswalk marking has been shown to not have a significant impact on pedestrian safety.[3]

Figure 4–1 displays more common crosswalk patterns, including the standard two parallel lines, continental, zebra and ladder markings.[1] The second intersection depicted in Figure 4–1 shows markings used with exclusive pedestrian phases described later in this chapter. Solid marking (crosswalk area completely marked) is also used. Figure 4–2 depicts another typical crosswalk application.

To increase the conspicuity of crosswalk locations and presumably improve the safety of pedestrian crossings, some states have experimented with unique crosswalk applications. Figure 4–3 shows a colored crosswalk application in Madison, WI.

4.1.1.5 Complementary Treatments

There are various measures that complement marked crosswalks, such as curb extensions, raised crossing islands, pedestrian traffic signals, traffic calming measures, crossing guards, crosswalk safety cones, actuated in-pavement crosswalk lighting, actuated lighted overhead signs, actuated regulatory signs and many others. Appropriate installation of these treatments at targeted locations may provide some level of increased driver awareness of pedestrians at the crosswalk.[7,8] A few examples are presented in this section.

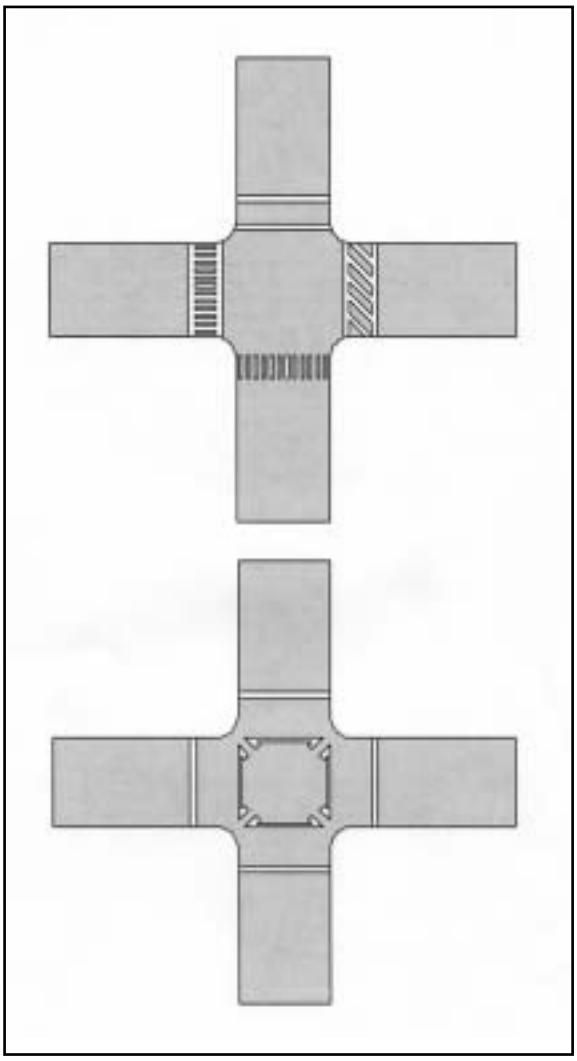

Figure 4–1: Typical Crosswalk Patterns
Source: David Noyce

Figure 4–2: Marked Pedestrian Crosswalk
Source: David Noyce

4.1.1.5.1 Pavement Markings

Detectability and awareness of traffic control features can be enhanced through pavement markings, ultimately improving intersection safety. Pavement markings provide numerous communication advantages since the markings are most commonly placed in the central vision area of motorists, unlike signs that are typically located in the periphery areas of vision. For example, additional safety for pedestrians can be gained through the use of STOP or YIELD lines 4 ft. in advance of and parallel to the crosswalk, indicating the point at which motorists are intended to stop.[1]

Guidelines for other pavement markings pertaining to the accommodation of pedestrians at intersections can be found in the MUTCD.[1] Linear pavement markings, such as crosswalks and bike lanes, can be supplemented by pavement marking symbols and text (also know as horizontal signing). For example, vehicle approaches to crosswalks often contain SCHOOL XING or PED XING symbol markings. Some agencies argue that pavement word and symbol markings should be used sparingly to retain effectiveness when used. Others believe that benefit is gained through additional information provided by these markings. A more detailed discussion of pavement markings is presented in Section 6.4.2 of Chapter 6 (Traffic Control Devices).

Some agencies have begun using sidewalk text to communicate with pedestrians. Instructions can also be found in the street at the curb departure point urging pedestrians to look for vehicles and proceed cautiously. An example of pedestrian crossing text is shown in Figure 4–4.

4.1.1.5.2 In-Pavement Flashing Crosswalks

In-pavement flashing (IPF) crosswalks consist of amber LEDs embedded into the pavement along the outer edge of a crosswalk with the LEDs aimed perpendicularly outward from the crosswalk. First used in California in the mid-1990s, IPF systems are now used at many uncontrolled marked crosswalks nationwide. These systems are most effective at improving motorists' response to pedestrians when

Figure 4–3: Colored Pedestrian Crosswalk
Source: David Noyce

This section is painted red.

Figure 4–4: Horizontal Signing for Pedestrians at Crosswalk
Source: Glenn Grayson; Meyer, Mohaddes Associates

they are set to flash only when actuated by pedestrians waiting to cross.[2,5] Actuation is usually provided by push-button or passive detection.

The proper application of in-pavement lighting at crosswalks has been recently added to the MUTCD.[1] The MUTCD requires that these devices only be used at marked crosswalk locations not controlled by STOP signs, YIELD signs, or traffic signals.

4.1.1.5.3 Flag Programs

Flag programs have become more popular in recent years. Any user wishing to cross the roadway takes a flag from a box located near the intersection crosswalk (Figure 4–5). The pedestrian raises the flag to increase his visibility and to inform an oncoming driver that the person intends to cross. The flag is returned to a box on the other side of the roadway upon completion of the crossing.

Observations of flag programs have found a higher percentage of motorists yielding to pedestrians. However, there are no definitive findings to suggest that flags improve safety at intersections for pedestrians. One common result of flag programs is the gradual disappearance of the flag supply. Local businesses have been used to support the program and keep a fresh supply of flags on hand.

4.1.2 Geometrics and Physical Features

4.1.2.1 Sight Distance

One design element that is commonly overlooked when considering pedestrians at intersections is pedestrian sight distance. Maintenance of sight lines from the crosswalk location at the intersection to an approaching vehicle is critical in avoiding vehicle-pedestrian conflicts. Guidelines on sight distance and vehicle stopping sight distance are found in local design guides and AASHTO publications.[9,10]

For roadways where on-street parking is allowed, a common guideline is to prohibit parking within 20 ft. of a crosswalk. Sight distance can be further improved by eliminating one additional parking stall or all parking within approximately 50 ft. of the intersection.

To encourage walking, many sidewalk designs now include landscaping, bus shelters, street furniture and kiosks. Although each of these items can enhance the aesthetics of the walking environment, they can also become sight distance barriers. Special care is required when considering both the short- and long-term effects of landscape improvements on visibility and sight distance. Guidelines are available for

Figure 4–5: Flags at a Pedestrian Crossing in Kirkland, WA
Source: 31/Matthew Ridgway

positioning street furniture and other objects for maximum visibility and minimum obstruction.[11]

4.1.2.2 Curb Ramps

Curb ramps provide a transition between the sidewalk and roadway or related surfaces. Schematic drawings of typical perpendicular and parallel ramps are presented in Figure 4–6.

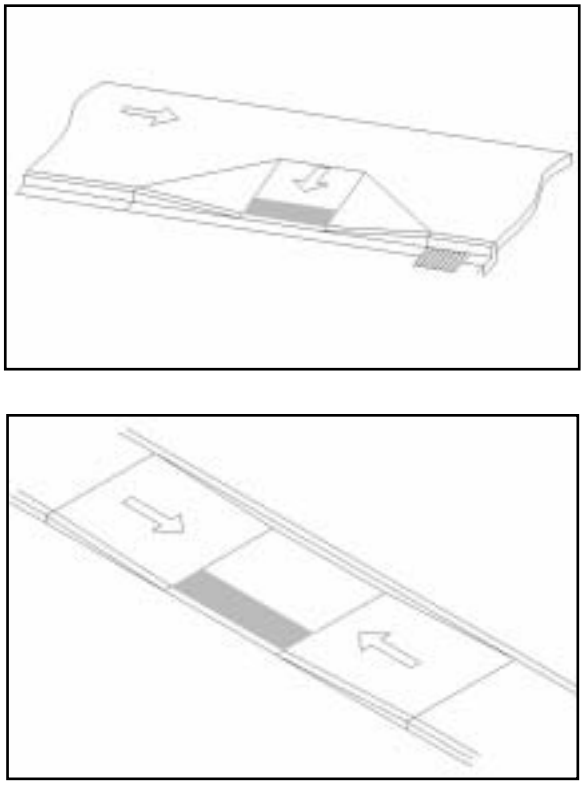

Figure 4–6: Perpendicular and Parallel Curb Ramp Designs
Source: U.S. Access Board

Improperly designed curb ramps can be a safety problem for all pedestrians and a barrier for pedestrians with mobility impairments. Curb ramp design details are found in the ADA Accessibility Guidelines for Buildings and Facilities (ADAAG) and Federal Highway Administration (FHWA) documents.[12-15] Many local agencies have also developed standard design guidelines for curb ramps. Typically, curb ramp designs will vary according to the following factors:

- Sidewalk width;
- Distance between edge of sidewalk and back of curb;
- Curb height and type;
- Curb radius;
- Intersection geometry;
- Sidewalk cross-slope and longitudinal grade;
- Roadway slope;
- Location of drainage inlets;
- Location of traffic control devices; and
- Crosswalk direction.

A level landing area is required at the top of each perpendicular curb ramp and at the base of each parallel curb ramp. A 24-in. wide detectable warning surface is required at the bottom of the curb ramp to provide a tactile cue of the boundary between the sidewalk and street (as shown in Figures 4–7 and 4–8).

Figure 4–7: Detectable Warning Surface at Parallel Curb Ramp
Source: U.S. Access Board

A manufactured detectable warning material added to the curb ramp provides the most effective means of maintaining a detectable warning surface. Figure 4–9 shows an attempt to form the detectable warning surface directly in the concrete curb ramp. In a short period of time, the paint wears away and the truncated domes begin to deteriorate and break off.

Direct alignment of the sidewalk and crosswalk is desirable. Typically, this requires two curb ramps at each corner. The direction and slope of the curb ramp may assist pedestrians with visual impairments in orientation and alignment guidance for crossing.

However, it is not always possible to accomplish this direct alignment at intersections with large radii.

Intersection corners with a single curb ramp in the center of the radius should be avoided for three principal reasons:

- Center curb ramps direct wheelchair users toward traffic and require a turn at the base of the ramp;
- Center curb ramps lead visually impaired pedestrians on an alignment outside of the crosswalk; and
- Many intersections have drainage structures near the center of the curb radius that can lead to ponding water and inlet grates with wheelchair and bicycle tire catches at the base of the curb ramp.

If a curb ramp design must meet a gutter, it should do so perpendicularly. A ramp that meets the gutter at an oblique angle may cause one wheel of a wheelchair to leave the ground.

Examples of curb ramp location problems are presented in Figures 4–10 through 4–14.

Figure 4–8: Detectable Warning Surface Using Brick Material at Curb Ramp
Source: U.S. Access Board

Figure 4–9: Stamped Detectable Warning Surface with Deteriorating Truncated Domes
Source: David Noyce

Figure 4–10: Undesirable Curb Ramp Location and Crossing Alignment
Source: David Noyce

4.1.2.3 Corner Radius

Corner radii at intersections have a significant effect on both vehicle and pedestrian users. Large radii allow for higher motor vehicle speeds and more efficient large vehicle turn maneuvers. Small radii reduce the travel distance required to cross the intersection, reduce the speed of turning vehicles, improve line-of-sight visibility between driver and pedestrian and provide all non-motorized users, particularly those with visual impairments, better direction through the intersection. Furthermore, small radii increase the corner space available for waiting pedestrians. Clearly, a balance between motor vehicle needs and pedestrian and bicycle needs is required when corner radii are selected. Figure 4–15 shows a typical small corner radius.

Figure 4–11: Curb Ramp Not Aligned with Crosswalk
Source: Janet Barlow

Figure 4–12: Difficult Sidewalk to Curb Ramp Cross Slope Transition
Source: Janet Barlow

Figure 4–13: Lack of Level Landing at Curb Ramp
Source: Michael Ronkin

Figure 4–14: Shifted Curb Ramp at Drainage Structure
Source: David Noyce

Figure 4–15: Intersection Corner Radius at Crosswalk Location
Source: David Noyce

Typical practice for determining corner radius involves selecting a design vehicle and applying a radius that meets its turning requirements (refer to Section 5.2.1 of Chapter 5 for additional discussion). Channelized right-turn lanes that provide motorists with a smoother and faster turn maneuver is another option used in areas with high right-turning traffic volume. The use of channelized turn lanes often includes a refuge island placed between the right-turn lane and adjacent through lanes (Figure 4–16). To avoid the potential usability and safety issues associated with channelized right-turn lanes, a crosswalk is necessary to delineate the travel path across the right-turn lane to the refuge island. A yield line or stop bar prior to the crosswalk may help drivers recognize this potential conflict point.[1]

4.1.2.4 Median/Refuge Islands

Refuge islands provide a location within the intersection where pedestrians can safely wait for vehicle traffic to clear before crossing. Raised medians or refuge islands are often provided at large multilane intersections. These islands can be effective treatments to reduce pedestrian and bicycle crashes on multilane roadways.[16] Raised medians are effective in improving safety for several reasons:

- Provide a refuge point for users to wait for the next appropriate crossing opportunity;
- Allow the intersection to be crossed in stages, separately for each direction of traffic;
- Reduce the number of conflicting vehicle maneuvers that must be considered (Section 5.2.1.4 of Chapter 5 discusses and illustrates this benefit of channelization);
- Break total exposure time and crossing distance into smaller segments;
- Direct pedestrians to the appropriate crossing location; and
- Provide a physical barrier from motor vehicle traffic.

Examples of median refuge applications are presented in Figures 4–17 through 4–19.

Figure 4–16: Refuge Island at Channelized Right Turn
Source: David Noyce

Figure 4–17: Median Refuge Island at Signalized Intersection
Source: David Noyce

Figure 4–18: Median Refuge Island at Unsignalized Intersection
Source: David Noyce

Figure 4–19: Median Refuge Island at Roundabout
Source: www.pedbikeimages.org. Photo by Dan Burden

Islands (with pedestrian push buttons) provide benefits at wide signalized intersections by allowing the opportunity for users to cross only part of the intersection during each walk phase. Signal cycle lengths can be reduced and the overall efficiency for all users of the intersection improved. Even if sufficient time is provided to cross the entire intersection, slow walkers may find it easier to cross in stages rather than crossing the entire street within the available pedestrian interval. An example of island push buttons is presented in Figure 4–20 and can also be seen in Figure 4–16. The application of island push buttons is also described in Section 6.4.3 of Chapter 6.

Figure 4–20: Island Pushbuttons for Pedestrian Crossing in Australia
Source: Janet Barlow

Islands designated for user refuge should be of sufficient size to provide a sense of security when placed near moving traffic. Minimum island sizes are provided in the AASHTO Green Book.[9] Additional width (6 ft. minimum) to accommodate the length of a bicycle or baby stroller should be considered.

Islands may provide a traversable path, be clearly marked and visible to the motorist and align with the natural path of the movements they are to serve. Islands must have an at-grade travel path through the island or appropriate curb ramps. For visibility and alignment purposes, painted medians are typically less effective than raised medians. A discussion on the use of refuge islands is found in ITE's *Design and Safety of Pedestrian Facilities*.[11]

For uncontrolled and mid-block pedestrian crossings, raised median or crossing island presence has been associated with significantly lower pedestrian crash rates at multi-lane roadways with both marked and unmarked crossings.[3] Similar analyses found that simple-painted (not raised) medians did not provide significant safety benefits to pedestrians when compared to having no median at all.

4.1.2.5 Curb Extensions

Curb extensions or bulbouts can reduce the effective street crossing distance for pedestrians and provide added space for installing appropriate curb ramps. Curb extensions are increasingly used at intersections

where on-street parking is present. Figure 4–21 displays an example of a curb extension.

Curb extensions are applicable at all intersection types including unsignalized intersections and midblock crossings where on-street parking is present. Curb-extension designs are site-specific but commonly extend through the parking lane to the edge of either a designated bike lane or travel lane.

Figure 4–21: Curb Extension at Unsignalized Intersection
Source: David Noyce

4.1.2.6 Access to Transit

Access to transit stop locations requires ample space for pedestrian storage. Queuing space must be able to handle peak hour demand and be accessible to all users. A minimum of 2 sq. ft. per person is required to provide a sufficient level of service.[17] The queuing area should not affect the flow of the primary pedestrian way.

Space must also be calculated for shelters and related street furniture. Research is being completed to explore design considerations and safety improvements for users of transit stops.[18] Figures 4–22 and 4–23 illustrate transit-loading examples.

Figure 4–22: Pedestrian Queue at Transit Loading Area
Source: David Noyce

Figure 4–23: Transit Stop with Associated Street Furniture
Source: David Noyce

4.1.3 Signing

This section deals specifically with signing associated with pedestrians at intersections. Signing associated with bicyclists is addressed later in this chapter in Section 4.2 and Chapter 6 which presents a complete discussion of intersection signing to accommodate motorists.

The MUTCD provides standards, guidance and support for the placement of traffic signs. Signs should only be used where they are justified by engineering judgment or studies. Refer to Section 6.3 of Chapter 6

for further discussion on the proper use of warrants, use of professional judgment, need for flexibility and mandate for uniformity in the application of traffic signs. Each category of traffic signs (regulatory, warning, guide) is treated separately in the following paragraphs.

Regulatory signs are used to give notice to traffic laws or regulations and include prohibitive signs, signs directing motorists to yield or stop for pedestrians, signs directing pedestrians to use a crosswalk and traffic signal signs (for example, signs at pedestrian push-buttons*). An example application of a regulatory sign targeted to motorists, but which directly affects pedestrians and bicyclists, is shown in Figure 4–24.

Figure 4–24: Bicycle and Pedestrian Regulatory Sign
Source: David Noyce

Some agencies use NO TURN ON RED signs to facilitate pedestrian crossings at signalized intersections. Although some jurisdictions report empirical evidence that suggests the prohibition of right-turns-on-red improves pedestrian safety, clear evidence of its safety effectiveness has not been documented. The use of this sign or any regulatory sign for pedestrian safety should be evaluated on a case-by-case basis.

Warning signs inform motorists of the potential for pedestrians at a downstream intersection. A field installation of a sample warning sign is presented in Figure 4–25 (and earlier in Figure 4–19).

To increase conspicuity and visual detection, warning signs can be mounted overhead in the motorist's primary line of sight. In some cases, the use of flashing beacons improves nighttime detectability. Figure 4–26 shows an example of an overhead pedestrian crossing warning sign.

Figure 4–25: Pedestrian Crossing Warning Sign
Source: David Noyce

Figure 4–26: Overhead Pedestrian Crossing Warning Sign
Source: David Noyce

* An ITE survey found that of all pedestrian-related signs, pedestrian pushbutton signs (at pedestrian-actuated signals) are the most beneficial to sighted pedestrians.[11]

Guide signs (for example, route markers, destination, distance, etc.) are typically not used or specified in any formal manner for pedestrians at intersections. The principal guidance information provided at intersections for pedestrians comes from street name signs. Signs should be readable to all users under all lighting conditions.

4.1.4 Traffic Signals

From the perspective of pedestrian needs, this section presents the following: MUTCD warrants for installation of traffic signals, signal timing and phasing concepts, pedestrian signal displays, optional methods for pedestrian detection and accessible pedestrian signals.

4.1.4.1 Traffic Signal Warrants

The MUTCD provides eight warrants for installing new traffic signals, two of which pertain to pedestrian considerations. These two signal warrants are not applicable at locations where the distance to the nearest signalized intersection along the major street is less than 300 ft., unless the proposed traffic control signal will not restrict the progressive movement of motor vehicle traffic. If a traffic control signal is justified by an engineering study, the traffic control signal should be equipped with pedestrian signal heads,[1] be traffic-actuated, include pedestrian detectors and coordinate with other signals if it is installed within a signal system.

The proper use and application of MUTCD traffic signal warrants is covered in detail in Section 7.1.3 of Chapter 7.

4.1.4.1.1 Pedestrian Volume Signal Warrant

The MUTCD specifies a traffic signal warrant based on pedestrian volume.[1] The pedestrian volume signal warrant is intended for application where the traffic volume on a major street is so heavy that pedestrians experience excessive delay in crossing the major street. The MUTCD allows for adjustments to the warrant criteria at locations where the average pedestrian walking speed is less than 4 ft./sec. (see Section 2.3 in Chapter 2 for a discussion of walking speeds).

4.1.4.1.2 School Crossing Signal Warrant

The MUTCD specifies a traffic signal warrant based on an analysis of the frequency and adequacy of gaps in motor vehicle traffic as related to the number and size of groups of school children at an established school crossing. A recommended method for determining the frequency and adequacy of gaps in the traffic stream is provided in the ITE publication *School Trip Safety Program Guidelines*.[19]

Even if an engineering study indicates that the warrant is satisfied, consideration should be given to the implementation of other remedial measures, such as warning signs and flashers, school speed zones, school crossing guards and grade-separated crossings.

4.1.4.2 Signal Phasing

Alternative signal phasing concepts to reduce pedestrian conflicts with motor vehicles are presented in Section 7.2 (Traffic Signal Phasing) in Chapter 7. Pedestrian signal indications include three distinct phases[1] as described below and as shown in the displays in Figure 4–27:

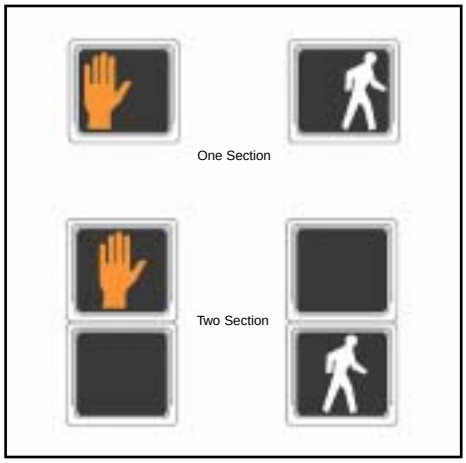

Figure 4–27: Pedestrian Signal Indications
Source: 1

- A WALKING PERSON display, indicating that pedestrians are permitted to leave the curb or shoulder;
- A flashing UPRAISED HAND, indicating that pedestrians are not permitted to leave the curb or shoulder, but those who have already begun crossing must proceed out of the traveled way; and
- A steady UPRAISED HAND, indicating that pedestrians are not permitted to enter the roadway in the direction of the signal indication.

A flashing WALKING PERSON display should not be used. Some agencies continue to use the words WALK and DON'T WALK as pedestrian indications and some flash the WALK indication warning pedestrians to look out for turning vehicles. Both of these practices are no longer permitted by the MUTCD.

Pedestrian clearance time (time immediately after walking person display has been terminated) should be sufficient to allow a crossing pedestrian, who entered the crosswalk during the walking person display, enough time to clear the full intersection. Pedestrians that do not enter the crosswalk before the onset of the flashing UPRAISED HAND should wait until the next signal cycle before crossing, although this is not well understood by all pedestrians. The pedestrian clearance time can be entirely contained within the motor vehicle green interval or may include the yellow change and all-red clearance intervals as well.[1]

Where pedestrian clearance time is sufficient only for crossing from the curb to a raised median or refuge island, additional supplementary measures should be implemented such as a median-mounted pedestrian signal and/or a pedestrian pushbutton detector. Examples are shown in Figures 4–16, 4–20 and 6–20. If such a mid-street detector is placed, it must be accessible per the ADA guidelines as described in Section 2.4 of Chapter 2.

One unique phasing arrangement that has been used to improve the safety of pedestrians at a signalized intersection is the exclusive pedestrian phase. This technique involves stopping all motor vehicle movements at the intersection and providing pedestrian phases on all approaches. Diagonal crossing is also allowed. Exclusive pedestrian phases can be effective at isolated intersections when large pedestrian volumes exist and when there are a high number of vehicle-pedestrian conflicts. Figure 4–28 shows a signalized intersection during an exclusive pedestrian phase.

Another technique that may be used to improve pedestrian safety is a leading pedestrian phase. In this method, the WALK indication is provided prior to the conflicting motor vehicle GREEN indication, allowing pedestrians to populate the crosswalk before vehicles are released. When pedestrian conflicts with right-turning vehicles is a safety problem, leading pedestrian phasing can be an effective technique. Signalization will be required to independently control the right-turn movement. Figure 4–29 shows an intersection with a leading pedestrian phase for right-turn traffic.

Figure 4–28: Pedestrians Making Diagonal Crossing During Exclusive Pedestrian Phase
Source: David Noyce

Figure 4–29: Leading Pedestrian Phase for Right-Turn Traffic
Source: David Noyce

4.1.4.3 Signal Timing and Clearance Intervals

Signal timing concepts and the means for calculating green intervals and phase change intervals are presented in Section 7.3 of Chapter 7.

The design of isolated or coordinated signal timing plans with various left- and right-turn phases while incorporating pedestrian timing is a complex task. Nevertheless, sufficient pedestrian crossing time should be provided at all signalized intersections where pedestrian movements regularly occur. At these locations, sufficient pedestrian crossing time should be provided during every cycle or through actuation of pedestrian detectors. Section 7.3.6 in Chapter 7 presents a detailed summary of signal timing practices to accommodate pedestrian crossings.

Care should be taken in the final selection of signal phase and cycle times to ensure that a balance exists between vehicle and non-motorized delays. Extensive delay for pedestrians can lead to an assumption that the signals are malfunctioning and can create potentially unsafe crossings without the WALK indication.

The time it takes a pedestrian to cross a street is based on the street width and the pedestrian's walking speed. Walking speeds vary widely as previously discussed in Section 2.3 of Chapter 2.

4.1.4.4 Signal Displays

Pedestrian signal displays are also governed by the MUTCD.[1] Pedestrian signal heads should be considered at each signalized intersection where pedestrian crossings take place. As a minimum, pedestrian signal heads should be used when pedestrians cannot see the motor vehicle signals to determine the right-of-way or where engineering judgment determines that pedestrian signal information will improve safety by reducing pedestrian-vehicle conflicts. According to the MUTCD, pedestrian signal heads shall be used under any of the following situations:[1]

- Traffic signal Warrant 4 (Pedestrian Volume) or Warrant 5 (School Crossing) is met;
- Exclusive signal phase is provided or made available for pedestrian movements in one or more directions with all conflicting motor vehicle movements stopped;
- Established school crossing at the signalized location; or
- Multi-phase signal indications (for example, split-phase timing) tend to confuse pedestrians guided by motor vehicle signal indications only.

A relatively new pedestrian signal display being implemented at many intersections includes a countdown function (Figure 4–30). The MUTCD allows a pedestrian interval countdown display to be added in order to inform pedestrians of the time, in seconds, remaining in the pedestrian clearance interval. Countdown pedestrian signals may be an effective way to communicate crossing times at multi-lane and complex intersections.

Figure 4–30: Countdown Pedestrian Signal Display
Source: David Noyce

The MUTCD provides additional detail on the above aspects of signal displays and for many other situations and must be consulted for specific details.

4.1.4.5. Pedestrian Detection

Pedestrian detection is often used at locations where pedestrian signal phasing is not required during each signal cycle (where the signal includes a pedestrian-actuated signal phase). The most common method of pedestrian detection is the pedestrian pushbutton. Such detectors should be capable of easy activation and conveniently located near each end of the crosswalk. Signs explaining the purpose and use should be mounted adjacent to or integral with the pedestrian pushbutton detectors. Examples of such signs are presented in Figure 4–31.[1]

Because proper pushbutton installation is critical to ensure optimal use, the MUTCD provides additional guidance. For example, when two crosswalks, oriented in different directions, end at or near the same location, pedestrian detectors and legends should be positioned to clearly indicate which detector actuates each crosswalk signal. Further, if the pedestrian clearance time is sufficient only to cross to a pedestrian refuge median and the signals are pedestrian-actuated, an additional pedestrian detector must be provided in the median. In some cases, an additional pole will be required to support the pedestrian push button at an appropriate location near the curb ramp. Figure 4–32 shows an example of additional poles for pedestrian applications.

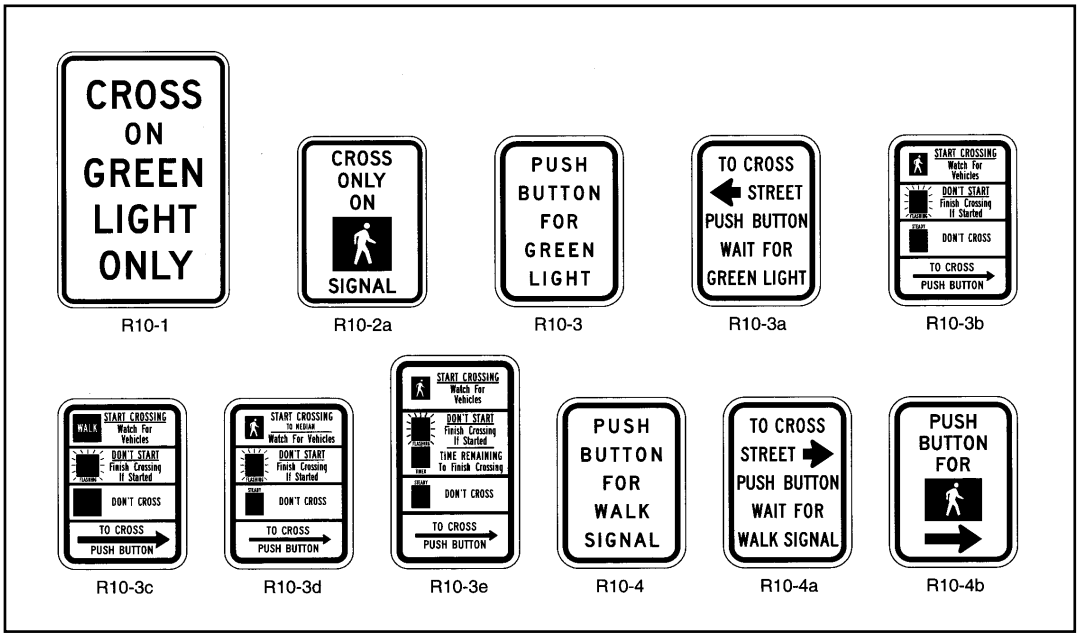

Figure 4–31: Signs Used Near or Integrally with Pedestrian Pushbuttons
Source: 1

Figure 4–32: Additional Pole Added to Support Pedestrian Pushbutton
Source: Lukas Franck

Innovative applications of existing technology being considered for the detection of pedestrians and bicyclists are described below.* A more detailed evaluation is presented in *An Evaluation of Technologies for Detection and Classification of Pedestrians and Bicyclist*.[20]

- Microwave Radar—Microwave detectors transmit electromagnetic radiation from an antenna towards the area of interest (for example, intersection corner). When a pedestrian or bicyclist passes through the monitored area, a portion of the transmitted electromagnetic radiation is reflected back to the antenna, initializing a detection.
- Ultrasonic—Ultrasonic detectors are similar to microwave detectors for passage and presence detection, but use sound waves of selected frequencies instead of microwaves.
- Video Image Processing (VIP)—A VIP system typically consists of one or more cameras, a microprocessor-based computer for digitizing and software for interpreting the images and converting them into pedestrian or bicycle data. The use of VIP for bicycle detection is currently being researched. Given positive results, this technology may be extended to pedestrian detection.
- Active Infrared—Active infrared detection zones are illuminated with low power infrared energy laser diodes. The infrared energy reflected from objects moving through the detection zone enables detection.
- Piezoelectric—Piezoelectric detectors are paving slabs with weight-sensitive rubber surfaces that are capable of detecting weight as light as 10 pounds.
- Several additional technologies are also available: acoustic, passive infrared, magnetic and traditional (inductive loops and pneumatic traffic classifiers) means.

4.1.4.6 Accessible Pedestrian Signals

Accessible Pedestrian Signals (APS) are devices that communicate information in non-visual formats such as audible tones, verbal messages and vibrating surfaces.[1] APS can provide important information to pedestrians including:

- Existence and location of the pushbutton;
- Onset of the walk and clearance intervals;
- Direction of the crosswalk;
- Location of the destination curb;
- Intersection geometry using maps, diagrams, or speech;
- Intersection street names using Braille, raised print, or speech; and
- Intersection signalization.

APS devices must include pushbutton-integrated devices with audible and vibrotactile indication of the walk interval, tactile arrow and tone or speech walk indication.[15] Locator tones are required where pushbutton actuation is required. Please note that much of the information in the following sections pertain to APS is drawn from *Accessible Pedestrian Signals: Synthesis and Guide to Best Practice*.[21]

* The application of most of these technologies for pedestrian or bicycle detection is still in the research and development stage. Some are proprietary products. Availability of these technologies for the current retail market is limited.

4.1.4.6.1 Types of APS

Four design types, plus various combinations, are currently available and categorized by the location and type of WALK indication provided.

Pedestrian head-mounted—The most commonly installed APS in the United States has a speaker mounted inside or in the vicinity of the pedestrian signal head, as illustrated in Figure 4–33. The APS emits a sound (for example, a bell, buzz, birdcall, speech message) during the walk interval of the signal only. The sound is directly audible, meaning it is heard by everyone in the vicinity (and thereby eliminates the need for receivers). This type of equipment typically has no locator tone or vibro-tactile indicator, but its volume level can be made responsive to ambient sound. Pedestrian head-mounted type signals with current tones have not proven to be localizable and do not provide directional information that many people hoped for.[21]

Figure 4–33: APS Speaker on Top of Pedestrian Signal Head
Source: Janet Barlow

Pushbutton-integrated—Pushbutton-integrated systems (with loudspeakers integrated into the pushbutton housing) are common in Europe and Australia and are now being installed in the United States (Figures 4–34 and 4–35). These systems have locator tones plus a WALK indication that may be a different tone, rapid repetition of the locator tone, or speech message. A tactile arrow is aligned with the crosswalk to show its direction. Further, either the arrow or the pushbutton may vibrate rapidly during the walk interval. Pushbutton-integrated APS, in its typical mode of operation and installation, is intended to be loud enough to be heard only at the beginning of the crosswalk, although the locator tone on the opposite curb becomes audible as the pedestrian approaches it.

Figure 4–34: APS Pushbutton Faces
Source: Janet Barlow; David Noyce

Figure 4–35: APS Installed with Proximity to Curb Ramp and Sidewalk
Source: Ed Paulis

Vibrotactile-only—For this type of APS, only walk information is provided by vibrotactile indication at the pushbutton location.

Receiver-based—Two APS systems communicate directly to personal receivers: (1) infrared transmitters mounted in or on pedestrian signal heads provide

speech messages at personal receivers and (2) LED pedestrian signal heads pulse to transmit a code to call up speech or vibrotactile messages at personal receivers.

4.1.4.6.2 Key Features of APS

WALK Indications—The most critical information provided by APS is the indication of the walk interval. Different APS devices and WALK indications may be needed for different situations. Vibro-tactile information is useful in combination with audible information for confirmation at particularly noisy intersections and for hearing-impaired individuals.

Volume—Volume adjustment is critical in successful operation of APS devices. The signal should be audible at the departure curb and responsive to ambient sound. In most circumstances, audible beaconing is not needed or desired for visually impaired pedestrians.

Pushbutton Locator or Tone—A pushbutton locator tone is "a repeating sound that informs approaching pedestrians that they are required to push a button to actuate pedestrian timing and that enables pedestrians who have visual disabilities to locate the pushbutton."[1] Pushbutton locator tones typically sound during the flashing and steady don't walk intervals. The locator tone informs pedestrians of the need to push the button and provides an audible cue to the location of the pushbutton along with the destination corner.

Tactile Arrow—Most APS devices that are integrated into the push button incorporate a raised (tactile) arrow that helps users know which crosswalk is actuated by the pushbutton. The arrow may be part of the pushbutton, above the pushbutton, or on top of the device. On some devices, this arrow also vibrates during the walk interval.

Pushbutton Information Message—A pushbutton information message is a speech message that provides additional information when the pedestrian depresses the button. The message may provide street names or information on intersection geometry or signalization. The pushbutton information message is provided from a speaker located at the pushbutton during the flashing and steady don't walk intervals only. The message is intended to be audible only to pedestrians at the pushbutton location. Pedestrians may be required to press the pushbutton for approximately 3 sec. to call up this additional speech message. Three seconds have been used to ensure that speech messages are not provided on random pushbutton presses and for those who do not require this information. Recent research has shown that a typical pushbutton press is less than 1 sec., and hence this 3-sec. time requirement for additional information may be reduced.[22]

Alert Tone—A brief burst of high frequency sound can be used to alert pedestrians to the exact onset of the walk interval. This may be particularly useful if the walk tone is not easily audible in some traffic conditions. The alert tone may encourage faster initiation of crossing.

Actuation Indicator—A light tone, voice message or other audible and visual indicators may be used to indicate that the pushbutton message has been accepted. Several APS devices emit an audible click or beep when the pushbutton is depressed. One device provides a speech confirmation message. If a light indicator is used, it is positioned at or near the pushbutton and remains illuminated until the WALK indication is illuminated. Although a light is helpful to persons with normal or low vision, persons who are blind require a tone. An example of a light indicator is shown in Figure 4–36.

Figure 4–36: APS with Actuation Indicator Light Illuminated
Source: Janet Barlow

Figure 4–37: Tactile Map on Side of APS Device
Source: David Noyce

Figure 4–38: Braille Label Located on Face of APS Device (just below the street name in large print)
Source: Janet Barlow

Tactile Map—The pushbutton-integrated signal can incorporate a raised schematic map showing what will be encountered as the pedestrian negotiates the crosswalk. This map is composed of changeable "slugs" inserted in the side of the pushbutton housing and must be set up for each crosswalk of the intersection. An example of a map is shown in Figure 4–37. This map shows that a divided roadway with two lanes of traffic in each direction is to be crossed. The pedestrian must travel across a curb ramp, bike lane, two traffic lanes, median, transit way, two traffic lanes and curb ramp to cross the roadway.

Braille and Raised Print Information—The street name controlled by a pushbutton can be printed in Braille above the pushbutton (Figure 4–38). For individuals who do not read Braille, large or raised print may be a viable alternative. The utility of this feature is currently limited because there is no standardized location for such information.

Extended Button Press—The extended button press feature actuates additional accessibility measures. The typical application requires the pushbutton to be pressed between 1 and 3 sec. for the activation of any or all of the following features:

- Accessible WALK indication;
- Pushbutton message identifying the intersection and crosswalk available during the solid or flashing DON'T WALK;
- Pushbutton message with intersection signalization and geometry information available during the solid or flashing DON'T WALK;
- Audible beaconing by increasing the WALK tone volume and the associated locator tone for one signal cycle, enabling visually impaired pedestrians to use the sound from the opposite side of the roadway for directional guidance;

- Audible beaconing by alternating the audible WALK signal back and forth from one end of the crosswalk to the other;
- Audible beaconing by providing the WALK signal at an elevated volume for one signal cycle from the far side of the street only; and
- Extended crossing time.

Passive Pedestrian Detection is available to call the WALK indication and extend the clearance interval. Passive detection of pedestrians for activating the locator tone may be helpful in reducing noise near an intersection. Available technologies for pedestrian detection are discussed earlier in this chapter in Section 4.1.4.5.

Remote Activation—Another available option for pedestrian detection is a handheld pushbutton that sends a message to the APS to call the pedestrian phase.

4.1.4.6.3 APS Device Installation

Installation of APS devices is similar to that for a traditional pedestrian pushbutton. Detailed installation and adjustment information is provided in *Interfacing APS with Traffic Signal Control Equipment*[23] and *Accessible Pedestrian Signals: Synthesis and Guide to Best Practice*.[21]

4.1.5 Sidewalks and Paths

Sidewalks and paths* are the primary travel way for pedestrians as they approach intersections in developed suburban and urban districts. Properly designed sidewalks provide mobility, accessibility and safety to all users. Sidewalks and paths should be made of smooth and durable material with appropriate slip resistance characteristics.

Sidewalks should be designed to have a usable clear width of at least 36 in. The U.S. Access Board's Draft Guidelines require a 48-in. clear width, which is consistent with AASHTO's recommendation in residential areas.[9, 13] Wider passing spaces need to be provided when pedestrian demand dictates. For example, a minimum width of 60 in. is generally recommended for sidewalks in residential areas. A minimum width of 96 in. is recommended in central business districts. Wider sidewalks are often required to maintain a minimum level of service (LOS) where there are greater pedestrian volumes.

Use of planting strips between the sidewalk and the back of a curb provides separation between the pedestrian and the roadway and improves safety and pedestrian comfort. Additionally, planting strips provide a location for placing utilities and other required objects. As presented in Figures 4–39 through 4–41, the placement of utilities in the sidewalk provides a safety hazard and impediment for pedestrians.

Figure 4–39: Utilities as Obstacles in Sidewalk
Source: David Noyce

* In this section, the term sidewalk is intended to mean both sidewalks and paths. Specific considerations for shared-use paths (i.e., with both bicyclists and pedestrians) are addressed later in this chapter in Section 4.2.4.

Figure 4–40: Pole as Obstacle in Sidewalk
Source: Michael Ronkin

Figure 4–41: Pole in Sidewalk Requires Pedestrian to Travel in Roadway
Source: U.S. Access Board

In general, sidewalks should be provided in all locations with any expected or recurring pedestrian demand. Generally, this includes public rights-of-way in all urban areas, commercial areas where the public is invited, all public areas and along access routes to transit stops. Sidewalks should be placed on both sides of the road in these locations. ITE's *Design and Safety of Pedestrian Facilities* and the AASHTO *Guide for the Development of Pedestrian Facilities* provide guidelines for installing sidewalks.[10, 11]

Wheelchair users and pedestrians with other disabilities must be considered when designing sidewalks. Guidelines for sidewalk side slopes and longitudinal grade are provided in numerous publications.[9, 12-15] In general, sidewalk cross slopes should be limited to 1:50 and longitudinal grades limited to 8 percent.

- In locations where matching the sidewalk to the back of curb leads to unacceptable cross slopes, a steep transition section can be used as long as the usable width exceeds the desired width (as illustrated in Figure 4–42). Steep transition sections do however create potential problems for pedestrians and wheelchair users who may drift off the sidewalk.
- ADAAG requires level areas at designated intervals and handrails when the grade is greater than 1:12 (8.33 percent) for more than 30 ft. However, the draft Public Rights-of-Way Accessibility Guidelines allow sidewalk grade to be the same as the adjacent street grade.[14, 15]

Figure 4–42: Sidewalk Sloped Transition Between Curb and Usable Sidewalk Area
Source: David Noyce

Sidewalk design requirements must be adhered to at all times. During construction or other events when temporary traffic control devices are in place, appropriate sidewalk accommodations must be established and maintained (Figure 4–43 and 4–44).

4.2 Design Elements Related to Bicyclists

The treatment of bicycle traffic at intersections depends largely on the type of travel lane. For shared lane and shoulder bicycle facilities, relatively few special accommodations are made aside from the

Figure 4–43: Temporary Sidewalk During Construction Activities
Source: U.S. Access Board

Figure 4–44: Temporary Sidewalk During Construction Activities
Source: Barbara McMillen

placement of bicycle route designation and guidance signs. On facilities with exclusive bicycle lanes or bike trails/paths, design treatments are more formalized and specific. Several basic principles to be followed when designing intersections to accommodate bicyclists are:[24]

- Avoid unusual or unexpected conflicts;
- Create a path for bicyclists that is direct, logical and close to the path of motor vehicles;
- Design the bicyclists' trajectory to be visible and movements predictable; and
- Minimize potential safety problems associated with the speed differential between autos and bicycles.

Specific design elements are discussed in the following sections.

4.2.1 Signs

A previous section of this chapter (Section 4.1.3) presents information on regulatory, warning and guide signs for non-motorized users of intersections (in general) and for pedestrians (specifically). This section provides examples of signs targeted to bicyclists, such as the regulatory signs in Figures 4–45, 4–46 and 4–47.

Figure 4–45: Regulatory Sign Applications
Source: David Noyce

Figure 4–46: Regulatory Sign Use
Source: David Noyce

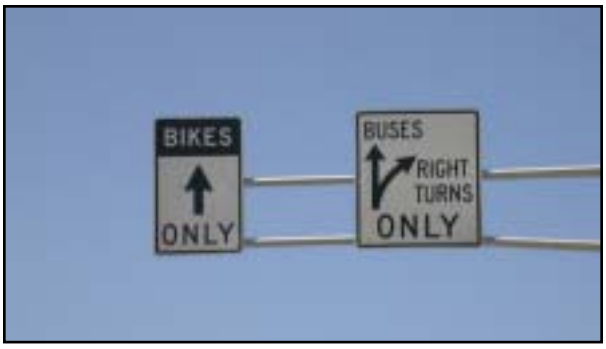

Figure 4–47: Regulatory Signs for Bikes, Transit and Motor Vehicles
Source: David Noyce

Street-bound bicyclists typically receive guidance information from the same signs as motorists. Trails and paths should also have guide signs installed at important junctions. Route signage can be used to provide bicyclists guidance on the most appropriate routes. An example of a guide sign is presented in Figure 4–48.

Figure 4–48: Example of Guide Sign for Bicyclists
Source: David Noyce

4.2.2 Bike Lanes

4.2.2.1 One-Way Versus Two-Way

Bike lanes are typically one-way facilities that carry bike traffic in the same direction as adjacent motor vehicle traffic. Bike lanes should be a minimum of 5-ft. wide and are usually demarcated by a 6-in. to 8-in. solid white line accompanied by appropriate words and symbols on the pavement.[1] Appropriate bike-lane signs should also be placed in accordance with the MUTCD.

Two-way bike lanes present a unique set of safety issues and for that reason their use should be limited. However, two-way bike lanes may be necessary in certain instances such as:

- On one-way streets;
- Along a boundary (expressway, lake, railroad) with no cross traffic; or
- Where crossing the street to ride with traffic is an extreme impediment.

4.2.2.2 Conflicts at Intersections

Bicyclists at intersections must deal with conflicts from both crossing and turning motor vehicle traffic, pedestrians and other bicyclists while traversing through an at-grade intersection. Designs to improve the operation and safety of the intersection should include positive guidance for all users.

Bike lanes should be terminated at crosswalks (marked or unmarked) and resume on the other side of the intersection. At low speed and moderate volume intersections, the bike lane may be discontinued ahead of the intersection so that bicyclists may merge and operate with traffic. At these intersections, bike turn lanes are unnecessary.

Conversely, some jurisdictions stripe bike lanes only at the intersection to create a lane for bicyclists. Intersection-only bike lanes should follow the same guidelines as standard bike lanes in the vicinity of intersections. The AASHTO *Guide on Bicycle Facilities* provides numerous marking examples.[25]

Intersections with multiple streets entering from different angles often result in confusion for users. In these cases, bicycle lanes may be striped continuously with dashes to guide bicyclists through a long undefined area.[24]

4.2.2.3 Motor Vehicle Right-Turn Lanes

If a right-turn lane is present for motor vehicles, special consideration must be given to the design of the bike lane and right-turn lane because through-bicyclists and right-turning vehicles will cross paths. Pavement marking and signing configurations that encourage crossing in advance of the intersection are preferable to those that force the crossing in the immediate vicinity of the intersection. These configurations have several advantages:[24]

- Conflict occurs away from the intersection where other conflicts occur;
- Motor vehicle drivers can easily pass bicyclists rather than ride side-by-side; and
- Through vehicles (including bicyclists) proceed to the left of right-turning vehicles.

Figure 4–49 provides an example of a bike lane transition using dotted line pavement marking.

Bikes lanes can continue up to the intersection and provide space between the through and right-turn lanes for through bicyclists. Figure 4–50 shows an example of this application.

Complex right-turn lanes add additional challenges to bicyclists. In designs where dual right-turn lanes or a combination right-turn/through lane exists, special consideration is warranted. Bicyclists who are forced to merge across multiple lanes of traffic (or across lanes where it is unclear of the motorist's intended direction) face potentially significant safety problems. Pavement marking and signing should be considered to communicate with all intersection users. MUTCD R4-4 and W11-1 signs along with various pavement marking patterns identified in the MUTCD have been successfully applied in similar conditions.

4.2.2.4 Left-Turn Lanes for Bicyclists

Where numerous left-turning bicyclists are present and a left-turn lane exists, consideration should be given to the placement of a separate left-turn lane for bicyclists that is adjacent and to the right of the motor vehicle left-turn lane. Bicycle detection may be

Figure 4–49: Bike Lane Transition to Accomodate Right-Turn Lane
Source: David Noyce

Figure 4–50: Bike Lane Between Through and Right-Turn Lane
Source: David Noyce

required to ensure that the traffic signal accommodates the bicyclist's movement. Illustration of a separate left-turn lane for bicyclists is shown in Figures 4–51 and 4–52.

4.2.2.5 Contra-flow

One approach for accommodating heavy two-way bike traffic in one-way street corridors is the use of contra-flow bike lanes. These lanes provide a dedicated area for bicycle travel in the opposite direction of motor vehicle travel. The bike lane should be a minimum of 5 ft. in width and be physically separated from the motor vehicle lanes through curb, barrier, or traffic control device. Figures 4–53 and 4–54 show a contra-flow bike lane in Madison, WI.

Separate traffic control is required for the bike lane as bicyclists are unable to observe the control messages in the opposite direction, as shown in Figure 4–55. Bicyclists must be able to turn into the contra-flow bike lane from either side street direction. From one side street approach, bicyclists must be allowed to turn left when motor vehicle left turns are prohibited. Similarly, bicycle right turns must be allowed from the opposite side street approach when motor vehicle right turns are not. Marked left-turn bike lanes and

Figure 4–51: Left-Turn Bike Lane Marking
Source: David Noyce

Figure 4–53: One-Way Roadway with Bike Lanes in Both Directions
Source: David Noyce

Figure 4–52: Left-Turn Bike Lane Marking and Signing
Source: David Noyce

Figure 4–54: Ground-Level View of Contra-Flow Bike Lane
Source: David Noyce

appropriate signs are required, as shown in Figures 4–56 and 4–57, respectively.

4.2.3 Signalized Intersections

Signalized intersections present numerous safety issues for bicyclists largely due to the potential for conflict with turning vehicles.

Bicyclists require the same level of guidance as motorists. Therefore, the level and quality of traffic control provided to motorists should also be available to bicyclists. Traffic control devices are especially important at signalized intersections and approaching bicyclists must be provided with the same visibility and functionality of traffic control devices as motor vehicle drivers.

4.2.3.1 Signal Timing

Section 7.3.6 in Chapter 7 presents a detailed summary of signal timing practices. Under normal traffic conditions, bicyclists can usually cross the intersection under the same signal phase as adjacent motor vehicles. Bicyclists are under the greatest risk during the change interval and actuated phases of low

Figure 4–55: Intersection Traffic Control for Contra-flow Bike Lane
Source: David Noyce

Figure 4–56: Lane for Bike Left-Turns Only
Source: David Noyce

Figure 4–57: Traffic Control for Bike Left-Turns Only
Source: David Noyce

traffic flow periods. Therefore, on shared roadways or roadways with bicycle lanes, signal timing should be designed to provide adequate:

- Change interval for bicyclists who enter at the end of green (accounting for bicyclist perception-reaction time and bicycle speed); and
- Total crossing time to accommodate bicyclists starting up on a new green.

Yellow change intervals timed for motor vehicle traffic (typically 3 to 6 sec.) are usually adequate for bicyclists. All-red clearance intervals are not typically required to accommodate bicyclists but are sometimes used to allow cyclists who entered the intersection on yellow to fully clear the intersection.

4.2.3.2 Bicycle Detection Technologies

Detection of bicycles at actuated signals is crucial for bicyclists' safety and compliance with traffic laws. Most properly designed vehicle detectors are capable of bicycle detection, including inductive loops and many video detection systems. Detectors should be located or aimed in the expected approach path of bicyclists. In certain locations, such as a wide intersection crossing a median, pushbutton detectors may be an acceptable detection alternative. Additional information on detection technologies is presented in Section 4.1.4.5 of this chapter and in *An Evaluation of Technologies for Detection and Classification of Pedestrians and Bicyclists*.[20]

4.2.3.3 Bike Boxes

Bike boxes are designated pavement areas between the intersection and the vehicle stop bar that only bicyclists can enter when traffic signals on the approach are red.[26, 27] To allow room for the bike box, vehicle stop bars are set back (advanced stop line) from the intersection. In most cases, an exclusive bike lane exists, allowing vehicles to pass the vehicle queue and move ahead into the bike box.

Bike boxes are designed to improve the safety of bicyclists by increasing their visibility in the roadway (by moving them ahead of the motor vehicle queue), helping them make safer turns at intersections and encouraging more predictable and consistent intersection maneuvers. A typical bike box design is presented in Figure 4–58.

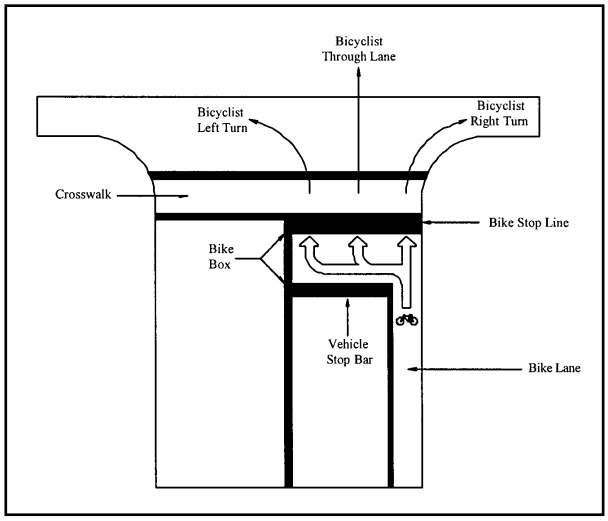

Figure 4–58: Bike Box Design
Source: David Noyce

4.2.4 Bike Trails and Paths (Shared Use)

Bike trails and paths are off-roadway bicycle facilities typically shared with other users such as pedestrians, joggers and skaters (Figure 4–59). The intersection of these trails and paths with roadways presents design challenges.

Figure 4–59: Shared Use Bicycle Path
Source: David Noyce

Because the alignment of bike trails and paths are sometimes independent of nearby roadways, path/roadway intersections may be unexpected by

bicyclists and motorists alike. At path/roadway intersections with limited visibility, advance warning signs and pavement markings are often installed. If bicyclists are required to stop at a path/roadway intersection, a STOP sign is required.[1] A YIELD sign should be installed where bicyclists have an adequate view of conflicting traffic as they approach the intersection and are required to yield the right-of-way to the conflicting traffic. Figure 4–60 illustrates a trail crossing at an intersection. The MUTCD provides additional information on the type and placement of regulatory traffic control devices.[1]

Refuge islands should be considered for trail/roadway intersections where one or more of the following conditions apply:[25]

- Trail crosses a multi-lane facility;
- High volumes of roadway traffic or high motor vehicle speeds create unsafe conditions for trail users;
- Roadway widths require crossing times greater than the available pedestrian crossing interval (at signalized intersections); or
- Slow-speed pedestrians are users of the trail.

Consideration should be given to make refuge islands wide enough to accommodate a full bicycle length, generally a minimum of 8 ft. If the intersection is signalized, pedestrian pushbuttons are desirable at each end of the trail crossing as well as on the refuge island.

4.3 Nontraditional Modes

There are numerous modes of transportation at intersections other than walking, bicycles and traditional motor vehicles. In-line skates and various types of human-powered and motorized scooters have become commonplace in the past decade.

Perhaps the next significant form of personal transportation to emerge will be the Segway Human Transporter (HT). The Pedestrian and Bicycle Council (PBC) of ITE recently completed an investigation of the Segway HT, a two-wheel device designed for individual travel. Use of the Segway HT has been targeted to both professional (for example, mail carrier, police) and personal markets. Because the Segway HT is capable of traveling at speeds greater than 12 mph, significant questions exist regarding how to safely and efficiently accommodate this user into the transportation system.

Figure 4–60: Trail Crossing at Intersection
Source: David Noyce

Table 4–1: Selected Examples of Segway HT Usage

Agency	Case Study
City of Seattle	Productivity enhancement for meter reading
United States Postal Service	Improved work environment; productivity enhancement
Michelin North America Inc.	Enhanced maneuverability within manufacturing plant and R&D facility
GE Plastics	Improved worker productivity/proximity
Delphi	Improved plant navigation and enhanced maneuverability
City of Atlanta (Ambassador program)	Visitor education and improved navigation
Atlanta Regional Commission	Worker movement in the downtown area of Atlanta
Georgia Power	Testing in various plant applications
Boston Police Department	Makes law enforcement officers more accessible and better able to navigate dense urban environment

Source: 28

Several pilot case studies have been performed on the use of the Segway HT, as documented in Table 4–1. The Segway HT introduces a unique challenge to the transportation profession. As with the initial introduction of other travel modes, current design practices do not necessarily provide a means of accommodating such a device. Several states have passed legislation allowing the Segway HT to operate as a "pedestrian" and travel on sidewalks. Refer to Section 2.6 in Chapter 2 for additional discussion of these unique "users" of intersections.

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chapter five

Geometric Design

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5.1 Introduction and Background

This chapter focuses on at-grade intersections, summarizing the general principles of intersection design and highlighting the application of techniques and practices that improve the safety and efficiency of intersection operations. The topic of intersection design and safety is broad and it is unrealistic to include the countless number of federal, state and local policies, standards and guidelines in a single chapter. Similarly, it is not possible to include the complete range of personal views, ideas, perspectives, philosophies and expectations related to intersection design and performance. It is, therefore, incumbent upon the readers of this chapter to view the ideas presented within the context of the needs and expectations of the local area as well as the latest practice standards, guidelines and research developments.

The text primarily addresses issues related to motor vehicle safety. This chapter should be read in conjunction with Chapter 4 in order to receive the complete picture of geometric design issues affecting all users of an intersection. Additional details on the use of design to enhance the mobility and safety of pedestrians can be found in the FHWA publication *Pedestrian Facilities Users Guide—Providing Safety and Mobility*.[5] Likewise, detailed and specific guidance for the design of bicycle lanes at intersections can be found in the AASHTO *Guide for the Development of Bicycle Facilities*.[6]

Numerous photographs are included in this chapter to illustrate concepts, not design details. Application of these concepts requires adherence to all federal and local design standards.

5.1.1 Functional and Safety Considerations

Intersections are often the controlling factor when establishing motor vehicle capacity of an urban roadway corridor.[2] Many intersections have been designed to present as few impediments to efficient through-travel as possible. However, intersections are also areas of concentrated conflicts between crossing, merging and diverging traffic streams, including pedestrian and bicycle traffic. As was mentioned in Chapter 1, the primary goal of intersection design is to maximize both safety and mobility. Like many highway features, safe and efficient traffic flow cannot be achieved by design alone—it requires a coordinated effort between design, traffic control, traffic and land use planning officials, as well as driver education and traffic enforcement.

Various references have suggested objectives, principles and guidelines that should be considered when designing intersections. Generally, these sources agree that five topic areas need to be considered during the design process:

- *Human Factors*, such as driver and pedestrian habits, reaction time and expectancy;
- *Roadway Users,* including the volumes and characteristics of all users of the intersection;
- *Physical Elements*, such as topography, development in the vicinity of the intersection, the angle of intersection between the roadways and various other environmental factors;
- *Economic Factors*, including the cost of construction, effect on adjacent residential and commercial properties and energy consumption; and
- *Functional Intersection Area*, including the approach and departure areas extending upstream and downstream from the intersection that are influenced by the various maneuvers within it.

Most design sources also agree that intersection designs should manage conflicting maneuvers to facilitate safe and efficient crossings and changes in direction while reducing the potential for crashes. This can be accomplished by:

- Minimizing the number of conflict points;
- Simplifying conflict areas;
- Limiting the frequency of conflicts; and
- Limiting the severity of conflicts.

It should be noted that many experts in the field of pedestrian safety believe that use of design features to enhance vehicular movement often will result in disincentives to pedestrians and can even lead to higher traffic speeds and volumes through intersections. Example measures that could have this effect include (1) improvements to clear vision sight triangles that in turn enable (and may even encourage) higher vehicle speeds and (2) the addition of turning lanes at intersections that lengthen pedestrian crossing distances, thereby increasing pedestrian exposure.

A recent effort to document relevant geometric and operational issues involved in the design of urban intersections produced the list of primary design considerations in Table 5–1.

5.1.2 Intersection Elements

Every intersection is unique in terms of the number and type of intersecting roadways, volume and composition of traffic, horizontal and vertical angles of the intersecting roadways, adjacent land-use development, available sight distances at the approaches and design users selected. Critical elements and the manner in which they guide the design of the intersection are summarized below.

5.1.2.1 Area

Intersections are defined in terms of physical and functional areas. The *physical area* of an intersection, shown in Figure 5–1, is defined as the area where intersecting roadways overlap. It is bounded on all sides by the edge of a pavement radius return and is commonly referred to as the *intersection threshold*.

Table 5–1: List of Areas of Concern within Intersection Design

Near Intersection
• When should another intersection's design or operation affect the design or operation of the subject intersection? How should it be treated?
• When should a neighboring railroad-highway grade crossing affect the design or operation of the subject intersection? How should it be treated?
• How to handle overlapping features (e.g., turn bays) or queue of cars?
• Interconnection with other signals
• Utilities
• Drainage
  o type of storm drains
  o relationship of drains to curb return
  o cross grades to prevent "bird baths"
 	
At Intersection
• Type of intersection
• Angle
• Grade
• Horizontal curve
• Distance to driveways
• Clear zones
• Sidewalks and pedestrian ramps
• Landscaping
• Sight distance
• Lighting
• ROW needs for mast arm placement
• Pedestrian facilities
 	
Users (other than trucks)
• Large trucks
• Buses
• Pedestrians
• Bicycles
• ADA
	Approach
	• Lane arrangement
	• Turn bays (right or left)
	  o Offset left-turn bays
	  o Length
	  o Deceleration into bay
	  o Approach taper
	  o Multiple lanes
	• Turning radius
	• Medians
	  o nose design
	  o location of nose
	• Pedestrian refuge
	• Bulbs
	• Channelization
	• Storage on through lanes
	• Signs
	  o Size
	  o Height of sign
	  o Height of letters on sign
	  o Self illumination
	  o Street names
	• Markings
	  o Crosswalks
	  o Stop lines
	
	Signals
	• Location of controller cabinet
	• Mast arm/span wire
	• Signal head
	• Footings
	• Pedestrian signal and buttons
	• Interconnection with other signals
	• Hardware
	• Detectors

Source: 3

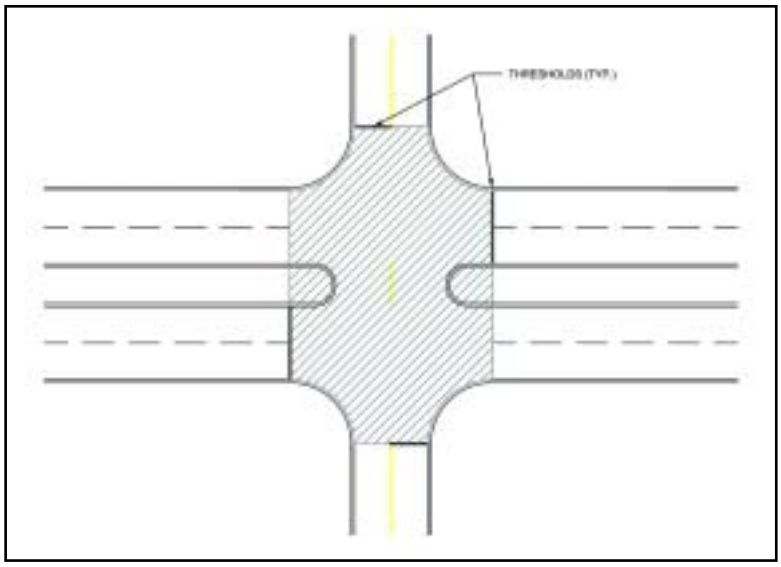


Figure 5–1: Intersection Physical Area

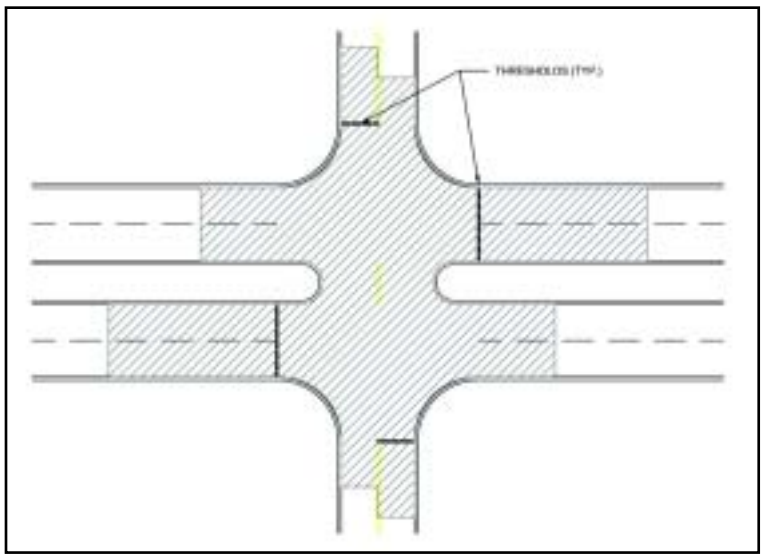


Figure 5–2: Intersection Functional Area

The *functional area* of an intersection extends for some distance in advance of the approach thresholds as shown in Figure 5–2.

In general, the upstream functional intersection area is comprised of three constituent parts: the distance traveled during the perception-reaction process, d_1; the distance required to decelerate while a driver maneuvers to a stop, d_2; and the distance required for queue storage, d_3.

The perception-reaction distance (d_1) is assumed to be the distance covered during a 1.5-sec. interval (2.5 sec. in rural conditions) while moving at the

Table 5–2: Functional Intersection Distances

Location	Speed (mph)	Distance Traveled During Perception-Reaction Time, d_1 (ft)	Maneuver Distance, d_2 (ft)	Perception-Reaction Plus Maneuver Distances, $d_1 + d_2$ (ft)	Queue Storage Length, d_3[a] (ft)	Upstream Functional Distance, $d_1 + d_2 + d_3$ (ft)
Rural	50	185	425	610	50[b]	660
	60	220	605	825	50	875
	70	255	820	1045	50	1095
Suburban	30	110	160	270	375[c]	645
	40	145	275	420	250[d]	670
	50	185	425	610	125[e]	735
Urban	20	45	70	115	500[f,g]	615
	30	65	160	225	500[f,g]	725

[a] Queue storage needs to be determined for each approach to each intersection using methods such as those discussed in Chapter 10.
[b] Minimum storage of two automobiles or one truck.
[c] Example of storage for 15 automobiles.
[d] Example of storage for 10 automobiles.
[e] Example of storage for 5 automobiles.
[f] Example of storage for 20 automobiles.
[g] Dual left-turn lanes can reduce the queue storage length.

Source: 10.Table 8–4, pg.134

approaching road's design speed. The deceleration/maneuver distance and queue storage length can vary significantly between urban, suburban and rural locations. In rural locations, where speeds are typically high and volumes typically low, most functional area distance is made of d_2. In urban and suburban areas, where the opposite is typically true of volume and speed, the majority of the functional area distance is made of d_3. Representative functional distances for various combinations of area type and speed are shown in Table 5–2.

A determination of the downstream functional area can be made using intersection sight distance requirements (see Section 5.2.1.2 in Chapter Five). This allows a driver to pass through an intersection before considering potential conflicts at a downstream intersection.

Recognition of these areas is important when analyzing sight distances, locating curb ramps, crosswalks, areas of on-street parking, bus stops and access/egress points to adjacent developments.

5.1.2.2 Approaches

Each roadway that enters an intersection forms an *approach*. Intersections that occur at the junction of two through highways incorporate four approach legs. In cases where one road dead-ends into the other, a three-leg, or T–intersection is formed. Occasionally more than two roads will intersect at a single point to form a complex multileg intersection. Although AASHTO recommends avoiding the creation of multileg intersections whenever possible, they are common in many urban areas.

Often, intersections occur between roadways of different functional classifications, for instance at the intersection of arterial and collector-distributor roadways. When this occurs, the higher classification, or *major roadway*, typically receives preferential treatment in design and control. This is logical given that the major road also usually has higher volume and operating speeds than the minor road. The differentiation between major roadways and *minor roadways* is important in design because it can determine the need for and placement of channelization devices, as well as the design of intersecting cross-slopes.

5.1.2.3 Control

The design of an intersection must take into account the type of control that will be utilized. Most intersections are controlled by a stop sign or traffic signal. The primary purpose of these devices is to assign right-of-way to the preferred movements of vehicles and pedestrians. A yield sign may also be used to assign right-of-way at intersections.

In certain low-volume conditions, such as those associated with local neighborhood streets or on lightly traveled rural roads, traffic movement at an intersection can be uncontrolled. Right-of-way is governed by accepted "rules of the road," which require the vehicle on the left to yield to the vehicle on the right if they arrive at approximately the same time.

The geometric design considerations for each of these control conditions vary, affecting sight distance requirements in each of the quadrants adjacent to the intersection. Specific information on these requirements is offered later in this chapter and a more detailed treatment of intersection signalization and control is included in Chapter 7 of this report.

5.1.2.4 Spacing

Another consideration that can affect the safe and efficient movement of motor vehicle traffic is the spacing of intersections. Proper intersection spacing is critical to provide coordinated signal timing.

In urban areas, the need to provide access to adjacent properties and cross-streets leads to closely-spaced signalized intersections. This can also be the case where there are large traffic generators located along high-volume, suburban corridors. However, frequent stopping for traffic signals and traffic queues from downstream intersections can result in travel delay and driver frustration. Generally speaking, intersection spacing of not less than 500 ft. for vehicular traffic is desirable.[3]

5.1.2.5. Other Intersection Types

Intersection designs vary based on the volume and mix of traffic at the junction. At the intersection of two high volume or high-speed roadways, a *grade separated intersection* may be warranted. Grade separated intersections may be as simple as bridges and tunnels that separate through traffic streams or as complex as *interchanges* that incorporate separate dedicated roadways for turning traffic. Simple grade separated intersections are highly effective for the movement of high through traffic volumes. However, they are also limited because they do not permit direct turning movements to the intersecting roadway. The major drawbacks to interchanges are construction expense and the need for acquisition of right-of-way.

Driveways also create intersections. Although a driveway's purpose is to provide ingress and egress to properties adjacent to the highway, it may still carry significant volumes of traffic and is often designed using geometric and control features similar to those of highway-to-highway intersections.

Another type of intersection is created at *highway-railroad grade crossings*. Because of the obvious hazards created by vehicle-train conflicts, these intersections deserve special design consideration in terms of sight distance, traffic control and vertical and horizontal alignments. The requirements for the design of highway-rail grade crossings are outside of the scope of this chapter. They can be found in both the AASHTO Green Book[1] and the *Railroad-Highway Grade Crossing Handbook*.[4]

5.2 Elements of Intersection Design

The following section summarizes the basic elements of intersection design for vehicles and describes how certain designs can improve intersection safety and mobility for vehicles. Issues related to pedestrians and bicyclists are touched upon but not described in great detail. A more extensive discussion of pedestrian and bicyclist needs is addressed in Chapter 4.

5.2.1 Horizontal Alignment

5.2.1.1 Approach Angle

The horizontal alignment of an intersection is a function of the alignment of the approaching road. Roads that intersect at acute angles make it difficult for drivers to see traffic approaching on some of the crossing legs, creating problems for large vehicle turning movements and extend both the time and distance required to cross the intersecting highway for both vehicles and pedestrians. As a result, it is strongly recommended that intersecting roadways cross at (or very near) right angles.[1]

The alignment of the approaching roadways, topographic features and adjacent development can occasionally make the creation of 90˚ intersections difficult to achieve. At locations where angles of 60˚ or less are present, a redesign of the intersection is encouraged. Redesign treatments generally fall into two categories: (1) those that increase the intersection angle through a redesign of the road alignments and (2) those that maintain oblique angles but attempt to lessen the hazardous effects of geometry. Like all design treatments, there are trade-offs between specific benefits and costs. Several of these treatments, along with their characteristics, are discussed below.

Generally, realignment options are substantially more expensive since they usually require the acquisition of right-of-way and the reconstruction of roadway approaches. Figure 5–3 illustrates five methods to address skewed intersections.

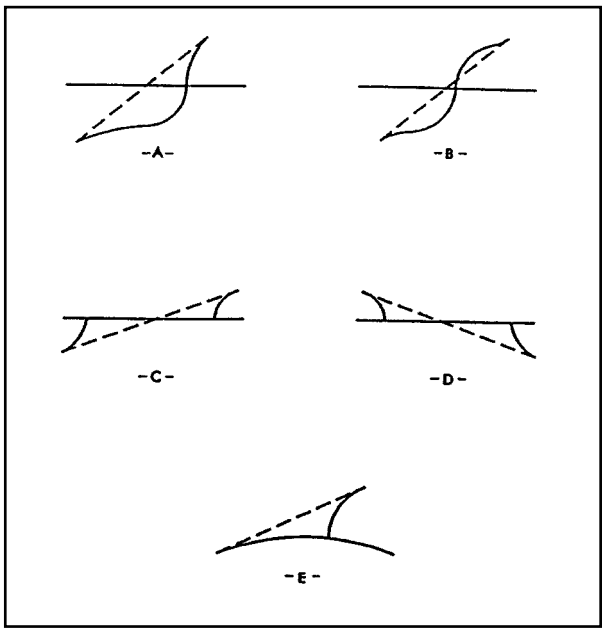


Figure 5–3: Intersection Realignment Alternatives
Source: 1

- Diagrams A and B involve a full realignment of one of the intersecting roadways, usually the lower classification of the two, to create a perpendicular crossing. A drawback to this treatment is that the addition of four curves to the minor road alignment near the intersection can be as significant of a hazard as the skewed intersection. For this reason it is suggested that these types of realignments incorporate speed reductions and advance warning signs.
- Diagrams C and D split the intersection into two separate three-leg perpendicular intersections. Although these configurations eliminate the problem of skew, they can have significant consequences on the operational efficiency of the minor road. In these designs all through traffic on the minor road is required to make two turns, one right and one left. High traffic speed on the major street and high traffic volume on the major or minor street can necessitate a long separation between the two intersections.[9, 10]
- Diagram E shows a treatment for skewed intersections on curved highway sections in which an intersection is created between the curve and a road extension from one of the tangents. Intersections on curved sections of highway should be avoided whenever possible. The combination of curved approaches and superelevated cross-slopes make this roadway and intersection design a complex undertaking.

Another option that may be more cost-effective when addressing problems associated with skewed intersections is to signalize the intersection. Signalization tends to lessen, though not eliminate completely, the potential for crashes associated with poor visibility during crossing and turning movements. Skewed crossings can make it difficult to align the signal faces with the approach lanes and often require the use of long visors, louvered signal faces and directional lenses.

5.2.1.2 Sight Distance

Intersection sight distance must be sufficient for all users of the intersection to anticipate and avoid potential conflicts with crossing and merging traffic streams. The dimensions of obstruction-free envelopes are a function of the physical conditions of the intersection, vehicle and pedestrian speeds and acceleration-deceleration distances.

This section highlights general considerations for various cases of intersection control. A detailed discussion of the specifics of each case is outside the scope of this book. Readers are encouraged to review the Green Book[1] and other relevant design resources included in the bibliography references.

Sight distance issues at signalized intersections are addressed further in Chapter 7. Sight distance issues for pedestrians and bicyclists are addressed further in Chapter 4.

Case A: Intersections with No Control

Sight distance provisions are based on rules-of-the-road practice, which "requires" vehicles on the left to yield to vehicles on the right when no control devices are present at an intersection. The no-control case requires clear sight envelopes that permit drivers to see other approaching vehicles at a point where they can stop or adjust their speeds to avoid crashes. If it is not feasible to provide sight distances under these conditions, consideration must be given to lower the approach speeds or install a stop sign on one or more of the approaches.

Case B: Intersections with Minor Road Stop Control

Stop controlled intersections require obstruction-free sight envelopes that permit drivers on the minor street to see vehicles approaching from the left and right on the major street. There are three sub-cases that may be considered at these locations.

- The first, *Case B1*, provides the departure sight triangle required for drivers turning left from the minor street onto the major street. In this case, adequate sight distance must be provided to the driver's left to allow the driver to cross these lane(s), and to the right to allow the driver time to accelerate the vehicle from a stop in order to not interfere with operations on the major road.
- *Case B2* is concerned with providing an adequate departure sight triangle for drivers turning right from the minor road onto the major road. The computational procedure is similar to Case B1 in that minor road drivers must complete the turn maneuver and accelerate without significantly affecting operating speeds on the major roadway. The assumed time gap required for right turns is typically less than that for left turns.
- In *Case B3*, sight distance is provided for major street crossing maneuvers from the minor street. In most cases the sight distances required for Cases B1 and B2 will provide adequate distances for crossing maneuvers. However, when turning maneuvers are not permitted, wide roads intersect, or when a high percentage of heavy vehicles exists, longer sight distances may need to be provided.

Case C: Intersections with Minor Road Yield Control

The sight distance requirements for yield-controlled intersections allow approaching vehicles to cross or turn without coming to a stop if no conflicting vehicles are approaching on the major road. The sight distances required under these conditions are in excess of those for stop control conditions (Case B) and are similar to those for uncontrolled intersections (Case A) in which only vehicles on the yield controlled approaches would need to stop or adjust speed.

Case D: Intersections with Traffic Signal Control

Obstruction-free sight envelopes should be provided at signalized intersections so that the first stopped vehicle on any approach is visible to the driver of the first stopped vehicles on all other approaches. Sight distance should also be available for left-turning vehicle motorists to see and select suitable gaps in the opposing traffic stream. If, however, the signal will be operated in a two-way flashing operation during periods of diminished volume, the sight envelopes defined in Case B should be provided on all of the minor approaches. In addition, any approaches with right-turn-on-red permissive movements should also incorporate the sight distances prescribed in Case B2.

Case E: Intersections with All-Way Stop Control

Sight distance requirements at all-way stop controlled intersections are similar to Case D in that the first stopped vehicle on any approach is visible to the driver of the first stopped vehicles on all other approaches. Warrants for the use of all-way stop control are included in the MUTCD.[8]

Case F: Left-Turn Locations from Major Road

Adequate sight distance should be provided at all points where left turns are (and, in the future, will be) allowed. AASHTO guidelines[1] state that an independent Case F evaluation is not required when stopping sight distance in both directions of the major

street and Case B and C sight distance have been provided from the minor street.

5.2.1.3 Corner Curb Radii

The ability of motorists to complete right-turning movements at intersections is affected by corner curb radii. The use of corner curb radii that are too small will require motorists to slow substantially to complete turning maneuvers. It may also result in particularly large trucks with large turning radii riding up over curbs, potentially harming pedestrians and damaging traffic control and landscape features. To that end, Section 7.4.3 of Chapter 7 addresses issues relative to the placement of traffic signal supports at intersections with small curb radii.

However, large corner curb radii may result in unnecessarily large intersections with wide-open areas of unused roadway. These can confuse motorists and will result in longer crossing distances for pedestrians. It is also important to keep pedestrians within the driver's cone of vision. Pedestrians end up farther away from stop positions especially when corner radii are made too large. Refer to Section 4.1.2.3 of Chapter 4 for a specific discussion of pedestrian needs relative to intersection curb radii.

The provision for adequate corner clearance may be achieved in several ways. AASHTO discusses the use of three different techniques including:

- Single radius joining the edge of pavement of the approaching and departing roadways;
- Taper-radius-taper design, in which the edge of the approaching lane is tapered into the curve, then tapers out of the curve into the departure pavement edge; and
- Three-centered compound curve, in which the corner curb is transitioned from a large radius to a smaller radius, then back to a larger radius before meeting the departure lane.

In areas with higher design speeds and truck volumes, corner curb radii in the range of 30 to 50 ft. are typically appropriate. In urban areas with a substantial pedestrian presence and limited truck traffic, curb radii in the range of 15 to 25 ft. are appropriate.[1]

The adequacy of corner clearance for turning vehicles can be determined during the design process using commercially available software. These programs can superimpose the path of a specified turning vehicle directly onto a design drawing. Figure 5–4 shows the results of such an analysis to determine the adequacy of a proposed intersection redesign to accommodate WB-50 design vehicles. The presence of an oblique angle intersection at this location led to concerns that large vehicles would not be able to complete right turning maneuvers. The turning analysis eliminated this concern and showed that a channelizing island would not be advisable at this location, despite the large amount of open paved area.

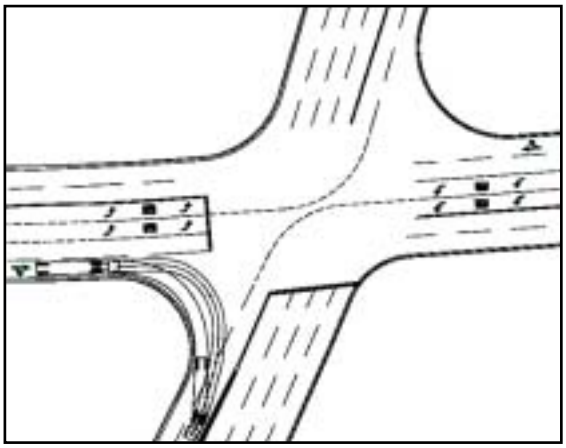


Figure 5–4: Sample Intersection Turning Analysis
Source: Laurence Lambert

5.2.1.4 Channelization

Channelization is defined by AASHTO as "the separation or regulation of conflicting traffic movements into definite paths of travel by traffic islands or pavement markings to facilitate the orderly

movements of both vehicles and pedestrians."[1] When used properly, channelization can simplify movements, increase capacity and improve safety within the vicinity of an intersection. Channelization accomplishes these by relocating and eliminating points of conflict while separating and restricting vehicular and pedestrian movements into specific and clearly defined paths. Channelization can be accomplished in several ways including islands, medians and various traffic control devices, such as flush-level pavement markings where it is not possible to use an island or where snow removal is a concern.

Like any design or control measure that restricts movement, channelization can have both positive and negative consequences. The benefits of channelization typically include a reduction in the number of vehicle conflicts and crashes; a decrease in crash severity; and a streamlining of vehicular movements at intersections, including the elimination of left turns in order to reduce delay to right turners and the prohibition of wrong-way entry. The principal drawback of channelization is the potential for added delay and travel time for some motorists because of the elimination of certain turn movements. Some types of channelization may also have significant negative impacts on pedestrians. The benefits and drawbacks of channelization are illustrated by the following application examples.

Discourage or eliminate undesirable or wrong-way movements—Channelization can be used to prohibit certain movements. Examples of this are "pork chop" and "right in-right out" islands as shown in Figure 5–5. Benefits of these islands also include the reduction of queued traffic in parking lots and exit driveways and the elimination of "dangerous" left turns onto busy streets.

Clearly define vehicle travel paths—One of the ways channelization can be used to define travel paths is by delineating exclusive turn lanes, as shown in Figure 5–6. In locations such as this, where a receiving lane is not available on the departure side of the intersection, an island can be used to prevent motorists from driving straight through the intersection. These features also eliminate confusion about which is the proper lane or direction of travel, particularly at skewed intersections or those with large open pavement areas.

Figure 5–5: Right-In/Right-Out Island
Source: Kenneth Shackman

Figure 5–6: Channelization to Delineate an Exclusive Right-Turn Lane
Source: Kenneth Shackman

Encourage desirable operating speeds—Channelizing features to "bend" or "funnel" movements can be used to slow traffic near merging, weaving and crossing areas. Channelization can also be used to open up travel and turn lanes to promote higher operating speeds in high-speed/high-volume locations, thereby keeping traffic moving and reducing the potential for severe crashes.

Separate points of conflict—To ease the driving task, channelization techniques such as adding islands near turning lanes will move the location of merging and diverging conflicts away from other areas of conflict closer to the intersection thresholds. This separation is particularly important in areas of overlapping maneuvers where channelization allows motorists to make one decision at a time. An example of an application of a separation island for a left turn lane is shown in Figure 5–7. The combination of different surface colors and textures at this location separates decelerating, slowing and stopped left-turn traffic from the through traffic lanes to reduce conflicts and rear-end crashes. This design can also be used to eliminate or reduce the potential for undesirable left turns from driveways immediately prior to the intersection.

Figure 5–7: Left-Turn Lane Separation Island
Source: Kenneth Shackman

Facilitate the right-angle crossing of traffic and flat angle merging maneuvers—At locations where roads intersect at flat angles, channelization can be used to control the angle of conflict by creating a perpendicular turning lane. An example application of this treatment is shown in Figure 5–8. At this location, a channelizing island has been used at an acute three-leg intersection to create a perpendicular intersection between the two roads.

Figure 5–8: Island Used to Create a Right-Angle Intersection

Provide a safe refuge for pedestrians and other non-motorized vehicle users—Islands can also shield non-motorized users within the intersection area, reducing users' exposure without significantly reducing the overall efficiency of vehicle operations. This concept is illustrated by the intersection in Figure 5–8. At this location, pedestrians are able to use the raised island as a stopping point between the approaching and departing street lanes during the short green phase given for minor street traffic. Pedestrian movements at this island are also aided by curb ramps located at the ends of each crosswalk. Applications of medians and refuge islands for the benefit of pedestrians are described in Section 4.1.2.4 of Chapter 4.

Locate and protect traffic control devices and facilitate the desired traffic control scheme—Channelization features, such as islands and medians, can be used to align turning movements, locate stop bars and help make traffic control features (for example, traffic signal heads) more visible. An example of this can be seen in Figure 5–7 where left-turn lane control has been installed on the median on the opposite side of the intersection. Channelization features can also be used to locate other roadside hardware such as traffic signal controller cabinets (Figure 5–8), signal support poles (Figure 5–6), luminaire supports and similar items.

Facilitate high-priority movements—Channelizing features can be used to designate high priority movements at intersections. In these instances the highest volume movements and/or the intersecting roadway with the highest functional classification with priority would receive preferential treatment. This type of treatment can also be used to maintain route continuity at intersection locations.

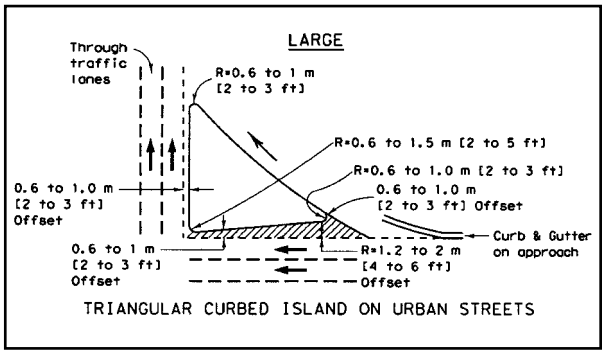


Figure 5–9: Design Dimensions for Large Corner Islands in Urban Conditions
Source: 1

For the most part, channelizing islands at intersections are unique features and each should be designed independently to fit a specific location and set of operating criteria. The principles that should be followed when designing channelizing islands include the following: [9]

- Channels created by an island at an intersection should appear natural and convenient to drivers;
- Island should be large enough to be effective (for example, general design dimensions of large corner islands for urban roadways are shown in Figure 5–9);
- Island should be clearly visible in all weather and lighting conditions;
- Island should favor major flow movements;
- Island should separate conflicts so that motorists, bicyclists and pedestrians need only to deal with one decision at a time; and
- Island should be designed with careful consideration given to the design speed of the intersecting roadways (for example, the approach end of the island should be delineated and offset from the roadway edge).

Another design consideration for islands is surface treatment. Islands may be paved or landscaped. Paved islands are typically easier to maintain, though they are generally not as aesthetically pleasing. The use of colors that contrast with the pavement surface is desirable because the color increases the visibility of the island. As a result, concrete islands are commonly used with asphalt roadways and vice versa. Brick pavers are also used in areas where aesthetics are important.

Other concerns include the need to adequately slope the surface of the island to facilitate drainage and keep the island free of sight obstructions and collision. All landscaping features should be kept below the clear vision envelope and should not incorporate other fixed hazards.

5.2.1.5 Turning Lanes

Intersections with high volumes of turning traffic may require exclusive-use turning lanes. In addition to providing a storage area for queued vehicles, turning lanes also provide an area outside of the through lanes for drivers to decelerate prior to making a turn. Because of the safety benefits of separating queued vehicles, some transportation organizations require the use of left-turn storage lanes at all signalized intersections. In cases where turning volumes are substantial and opposing through traffic is high, dual (and occasionally triple) turn lanes are used. The disadvantages of multiple turn lane approaches are the additional right-of-way required for construction, added crossing distance and exposure for pedestrians and additional green time required for side street pedestrian clearance.

The Highway Capacity Manual[2] suggests the use of a single left-turn lane at signalized intersections for left-turn volumes greater than or equal to 100 vehicles per hour (vph), a dual left-turn lane for left-turn volumes greater than or equal to 300 vph and right-turn lanes for right-turn volumes greater than or equal to 300 vph.[2]

Table 5–3: Left-Turn Lane Storage Requirements Based on Traffic Volume

Unsignalized Intersection	Signalized Intersection	
	Permitted-Only Left-Turn Phasing	Protected/Permitted- or Protected-Only Left-Turn Phasing
L = f * V * (120/3600) * l	L = f * V * (C/3600) * l	L = f * V * (C/3600) * ((C-g)/C) * l

Legend:

L = required storage length in feet

f = storage length peaking factor
- f = 2.00 for V < 300 vph
- f = 1.75 for 300 ≤ V ≤ 500 vph
- f = 1.50 for 500 ≤ V ≤ 1,000 vph
- f = 1.25 for V > 1,000 vph

V = design hourly turning volume in vehicles per hour

C = cycle length in seconds

g = effective protected green time for turning movements in seconds (may include an additional two seconds to reflect vehicles that "sneak" through at the beginning of the clearance interval; see Section 7.2.2 of Chapter 7 for additional discussion on this topic)

l = average vehicle length in feet (typically, use 25 ft.)

Source: Kenneth Shackman

Table 5–4: Left-Turn Lane Storage Requirements Based on Design Speed

Design Speed (mph)	Minimum Storage Length (ft.)
30	100
40	125
45	150
50	200
55	250
60	300

Source: Kenneth Shackman

Figure 5–10: Left-Turn Lane at a Rural Unsignalized Intersection

There are numerous methods for determining appropriate turning lane lengths. One example is a method used by Ken Shackman (formerly of Pima Arizona County DOT) for determining the storage length requirements of turn lanes at signalized and unsignalized intersections. This method uses the greater of two values, one based on motor vehicle traffic volumes (calculated as shown in Table 5–3) and one based on motor vehicle design speed (listed in Table 5–4).

Turning lanes can also yield safety benefits at low volume and unsignalized intersections by removing stopped and slowed vehicles from the through traffic stream. This can reduce the occurrence of rear-end, side-swipe and run-off-the-road types of crashes. An example of a turn lane at a low volume rural intersection is shown in Figure 5–10. Here, a separate left-turn lane has been constructed to accommodate left-turning traffic. Because of the moderate to low volumes present in this area, the storage length of the turn lane is 50 ft., the minimum local standard.

A more recent treatment of left-turn lanes at intersections, designed to enhance safety, is the use of median left-turn lanes at the approach threshold.[3] Although primarily for use on divided highways with adequate medians, the positive offset shifts queued turning traffic away from the through lanes so that left-turning drivers had a less obstructed view of opposing through and right-turning traffic. An example of this concept using raised islands is shown in Figure 5–11.

Figure 5–11: Offset Opposing Left-Turn Lanes on a Divided Highway

The proper accommodation of bicycle turning movements can be a critical issue at an intersection. Right-turning motor vehicles must cross paths with through bicyclists. Signing and pavement markings help control and guide conflicting movements. Figures 4–49 and 4–50 in Chapter 4 illustrate this concept. Left-turning bicyclists position themselves on the right side of left-turn lanes. If bicycle volume is high, these areas can be designated explicitly for bicyclists by pavement markings and signs (Figures 4–51 and 4–52).

5.2.2 Vertical Alignment

The task of designing vertical alignments in the vicinity of intersections is more complicated than road segments because these alignments must accommodate vehicle and pedestrian movements from multiple directions. Intersection profiles should be designed to promote both safety and mobility by maximizing sight distances and facilitating vehicle braking. Grades should be kept as flat as possible without affecting the ability to efficiently drain the intersection area. The following sections discuss the requirements for intersection profile design and highlight techniques that can be used (or avoided) to enhance the quality of the design.

5.2.2.1 Profile Grades

The ability of motorists in passengers cars to stop and accelerate on grades of 3 percent is not significantly different from their ability on level surfaces. However, grades steeper than 3 percent can increase the distance needed to bring vehicles to a stop and degrade the ability of motorists, especially those driving large trucks, to accelerate from a stop. It is recommended that profile grades steeper than 3 percent be avoided on intersecting roadways and that grades should not exceeded 6 percent.[1]

On steep approach grades, it is desirable to include flatter profiles immediately leading to the intersection thresholds. These areas, commonly known as "storage platforms," provide a flatter storage area for stopped vehicles and reduce the abruptness of profile changes within the intersection. An illustration of this concept at an intersection with very steep approach grades can be seen in Figure 5–12. This photograph taken in San Francisco, CA, shows the use of short monotonic vertical curves in advance of the intersection.

Figure 5–12: Intersection with Steep Approach Grades
Source: David M. Wickens

5.2.2.2 Intersecting Grades

Intersecting roadway cross slopes create a design challenge. Because the pavement cross slopes of the intersecting roadways meet at opposing angles, care must be taken to ensure rideability for vehicles and walkability for pedestrians.

Although both roadways have to be considered, it is typically the cross slope of the major highway that is assigned a higher priority. The cross slopes of the major road are usually carried through the intersection and the minor road is adjusted to fit it. It is common practice, however, to flatten or "warp" the profiles and cross slopes of both roads within the intersection so that they do not create a ramping effect in one or more approach directions. This is typically accomplished by rounding the pavement cross slopes to form a gently sloping "tabletop."

Grade and cross slope design should facilitate the drainage of surface runoff at intersections. This starts by guiding flow in the predominant direction of fall on the intersecting roadways while eliminating, or at least minimizing, sheet flow across the intersection. The tabletop design helps to direct surface runoff to the outsides of the intersection.

The design of grades, cross slopes and drainage features can also be complicated by divided highways, medians and other channelizing features. In each case, it is important to consider both the amount and direction of runoff to ensure that no water will be trapped or impounded in low spots at the edge of these features.

5.2.3 Cross Section

The cross-section design of roadways encompasses the layout of lanes, shoulders, medians, sidewalks, curbs, embankments, drainage features and pavement thickness. Cross-section design at intersections includes many of these same features, although the design is largely guided by the cross section of the intersecting roadways. The AASHTO Green Book[1] provides a comprehensive and detailed list of appropriate design dimensions for all of these cross-section features.

The accommodation of non-motorized users must also be incorporated in the intersection cross section design. Intersections in urban areas must include sidewalk areas and curb ramps. In pedestrian-oriented areas, intersections can be designed with narrowed approach widths to form nubs, bulbouts, bump-outs and knuckles. These narrowing techniques provide multiple benefits in that they tend to (1) reduce operating speeds in the vicinity of intersections, (2) provide additional space for pedestrians to queue prior to crossing and (3) reduce the length of the pedestrian crossing. An example of a bump-out can be seen in the upper left quadrant of the intersection in Figure 5–13. Refer to Chapter 4 for additional discussion and presentation of effective design treatments for pedestrians and bicyclists at intersections.

Figure 5–13: Cross-Section Enhancement at a Pedestrian High-Volume Intersection
Source: www.pedbikeimages.org. Photo by Dan Burden

Medians at intersections act similar to islands in that they separate opposing traffic streams, reduce pavement area, provide areas for pedestrian refuge

and provide an area to locate various traffic control and lighting features. Another significant benefit of medians is that they can be used to control access by eliminating left turns into and out of adjacent properties. Intersection medians also have some disadvantages. If not designed with embedded left-turn lanes, wide medians can cause left-turn interlock, a condition that occurs when opposing left-turn movements cross paths. Other safety and operational disadvantages of medians at intersections include an increased potential for wrong-way entries and increased minimum green times for pedestrian crossings. The Green Book[1] describes the design of several features of intersection medians, including width and sloped treatments for approach noses.

5.3 Unconventional Design Configurations

To improve both the operational efficiency and safety characteristics of intersections, engineers continually develop innovative design and control strategies. This section highlights the general safety and operational characteristics, benefits and costs of several unconventional designs for arterial/collector intersections. These designs are regarded as "unconventional" because they incorporate geometric features or movement restrictions that are not permissible at standard four-leg and three-leg at-grade intersections. Such elements include the elimination or relocation of various through and turning maneuvers and the use of indirect turning movements.

The common theme of most of these designs is to improve the overall operation of the intersection by favoring heavy volume arterial street through movements. Typically, these benefits are created by moving or eliminating conflicting left-turn movements to and from the minor cross street, thereby reducing the number of signal phases (and associated start delay and clearance times) and allowing the intersection to operate in a simple two-phase operation. Not surprisingly these benefits sometimes accrue at the cost of increased delay, travel times and travel distances for the major street left-turning traffic and for some minor street vehicular and pedestrian movements.

The following sections describe the basic layout and operation of these designs and the benefits and drawbacks of each with respect to analogous four leg at-grade designs. The sections also discuss the locations and conditions under which the designs are thought to be most appropriate. The information presented here has been summarized from numerous research and practitioner reports. These are included in the reference and bibliography sections at the end of this chapter.

5.3.1 Median U-Turn Intersection

The primary objective of the median U-turn design is to remove all left-turn traffic from the main intersection. In this configuration all left-turn movements are converted to right turns at the intersection using a uni-directional median crossover to make a U-turn on a major highway. Figure 5–14 shows a schematic diagram of a typical median U-turn intersection.

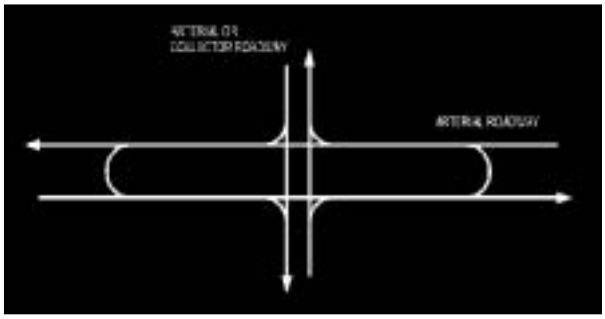


Figure 5–14: Median U-Turn Intersection Diagram

This design type favors the major street through movement because time from the signal cycle does not have to be allocated to protected left-turn phases. Since it is possible to control the median U-turn intersection with a two-phase cycle, this design facilitates coordinated signal progression along high volume arterial corridors. This design also removes or relocates all of the conflicts normally associated with left-turn movements. Thus, crashes *directly* associated

with left-turn movements are eliminated. It should be noted that the exposure to crashes associated with higher right turn and U-turn volumes will likely increase, although these crashes are generally less severe than left-turn crashes.

One disadvantage associated with the use of a median U-turn intersection design is its potential for added stopping and delay for left-turning traffic. Despite this fact, this design has been shown to improve total intersection delay and travel time conditions under certain volume conditions. Another disadvantage is that a median U-turn design requires large rights-of-way along the major street (in fact, AASHTO recommends a 60 ft. median to accommodate large trucks). This design also requires the use of multiple signal installations (typically three, one for the main intersection and one for each of the two median cross-overs) instead of just one.

From a non-motorized user standpoint, this design presents fewer threats to crossing pedestrians than a standard four-leg intersection. Although this design requires more time to cross the major roadway, the median can serve as a refuge area for pedestrians. It should also be noted that the longer crossing distances could also require longer minimum green times or two-cycle pedestrian crossing signals.

Median U-turn intersections are most appropriate for high volume arterial roadways with medium to low left-turning traffic and within corridors where it is possible to acquire the right-of-way required for its construction.

5.3.2 Jughandle Intersection

The principle of the jughandle design is to remove all turning traffic (including right turns) from the main intersection by shifting traffic from major street approaches and onto adjacent ramps as shown in Figure 5–15. Turning maneuvers are completed at an intersection created between the ramp and minor roadway. Separate ramp roadways are used for the two major street approaches and (if acceptably low volumes are present) left turns from the minor street are permitted onto the major roadway.

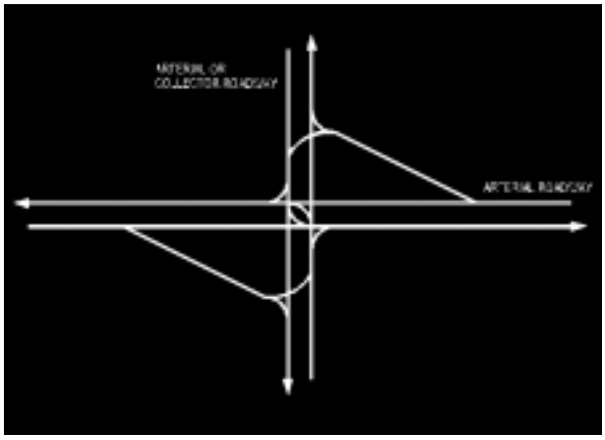


Figure 5–15: Jughandle Intersection Diagram

Like other unconventional intersection designs, this configuration favors major street through movements, thus it is best suited for high volume arterial roadways with moderate to low left-turn volumes. Because it does not require median crossover maneuvers, it can also be used in narrower rights-of-way. Its main disadvantage is inconvenience to left-turning traffic in the form of possible additional travel time, distance and stops. The costs of right-of-way to construct the jughandle roadways can also be a drawback. From a pedestrian standpoint, this design requires additional roadway crossings because pedestrians along the major and minor roadways are also required to cross the ramp intersections. Each additional crossing increases pedestrian exposure to conflicts.

In the United States, jughandle intersections have been most widely used by the New Jersey Department of Transportation. These intersections have been in operation for decades on hundreds of miles of arterial highways in New Jersey. Simulation studies of the jughandle configuration show that

while its performance is similar to that for median U-turn and conventional designs, it consistently performs worse than those designs in terms of overall travel time.[13]

5.3.3 Left-Turn Loop Intersection

A variant of the jughandle design is the "left-turn loop" intersection. In this design, left turning maneuvers from the major roadway are moved to a loop and ramp in one of the intersection quadrants. As shown in Figure 5–16, drivers from one of the major approach directions complete left turns in advance of the main intersection. These left turns can usually be accomplished without the need for signal or sign control because there are a number of readily available gaps that result from the signal control at the main intersection. Drivers from the opposing direction complete left turns on the loop ramp.

This design has been used by the Michigan Department of Transportation on high volume corridors at intersections with heavily traveled minor cross streets. Similar to previous designs, the left-loop configuration removes major street left-turn conflicts from the main intersection and permits the intersection to operate in a two- or three-phase sequence. Despite additional travel distance, left-turn maneuvers on the loop road can be completed at a relatively high speed and are not interrupted or opposed by other traffic streams.

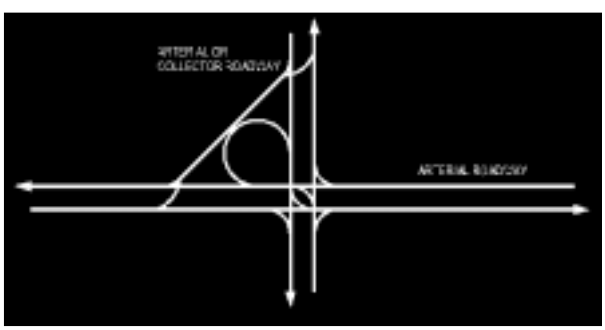


Figure 5–16: Left-Turn Loop Intersection Diagram

Two disadvantages of the left-turn loop design are that it requires two left turns from one of the major street approaches and left turners from the other major approach direction must cross the intersection twice. This design renders one of the intersection quadrants un-developable.

From a pedestrian standpoint, the design requires additional roadway crossings for some pedestrians (those in the upper-left quadrant of Figure 5–16). For some pedestrians, the amount of exposure to conflicts does not change.

5.3.4 Crossover Displaced Left-Turn (XDL) Flow Intersection

The crossover displaced left-turn (XDL) intersection (also known as *two-phase enhanced at-grade intersection* and *continuous flow intersection*) shifts the left-turn traffic from the approaches to the main intersection across the opposing traffic lanes prior to the main intersection as illustrated in the schematic diagram of Figure 5–17. Left-turn maneuvers are then completed simultaneously and unopposed with the accompanying and opposing through movements. The displacement of left-turn lanes allows the main intersection to operate on a two-phase signal. If right-of-way availability or other costs are an issue, ramps in one or more of the quadrants can be eliminated in favor of a three-phase signal.

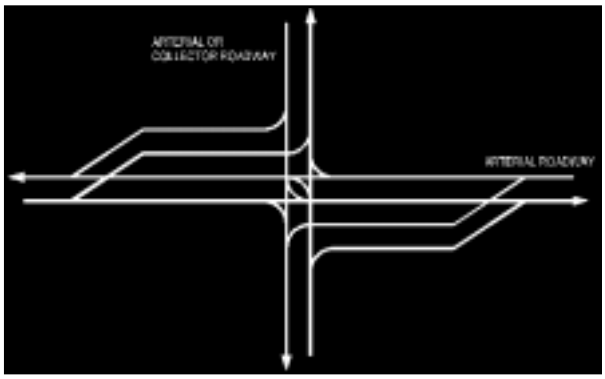


Figure 5–17: Crossover Displaced Left-Turn (XDL) Flow Intersection Diagram

Under high volume conditions, left-turn crossover movements prior to an intersection can also be signalized. This signal will not necessarily impact the overall operation because the crossing phase can be

coordinated with the signal at the main intersection. Since this design does not require wide medians for crossovers, it can be used in narrower corridors.

The XDL intersection has some disadvantages. Because motorists need to be aware of the need to make left turns prior to the intersection, clear guidance must be given to warn motorists of the impending roadway and guide them into the appropriate lanes. Pedestrians will also need to be guided and informed of vehicle approach direction because of multiple lane crossings within the intersection.

The XDL intersection is most appropriate for high volume arterials with few needs for U-turns. Another important consideration is the level of development near the intersection. Crossover displaced left-turn intersections do not provide easy access to and from adjacent properties because of the locations of the left- and right-turn lanes.

Although XDL intersections have been used for about 40 years, there have not been a large number of applications of this design in the United States. Several XDL intersections have been recently constructed in Mexico, one was constructed at a T-intersection with ramps in a single quadrant on Long Island, NY in 1994 and another was constructed in Maryland in 2000. Several states (for example, Ohio, Mississippi, California, Arizona, Nevada) have seriously investigated the use of XDL intersection designs, as have 10 other North American cities.[14]

5.3.5 Split Intersection

The split intersection separates directional traffic flows on a major highway into two offset one-way roads as illustrated in Figure 5–18. The resulting configuration is similar to an at-grade diamond interchange without a separate bypass for through traffic.[15]

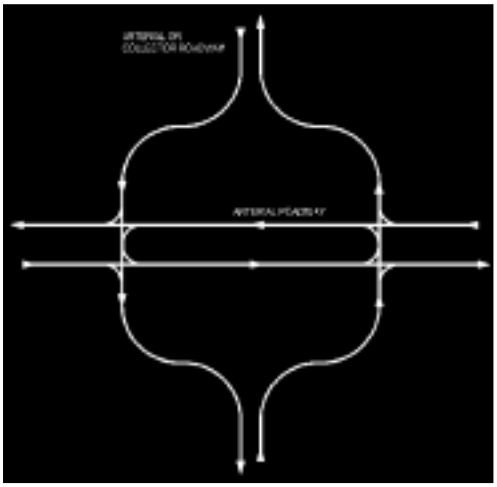


Figure 5–18: Split Intersection Diagram

The advantages of split intersections are an increase in capacity and a reduction in overall delay[15,16] compared to a conventional four-approach design. At a cycle length of 120 sec. and maximum turning volume, the capacity of a split intersection is approximately 35 percent higher than that of a conventional configuration. The majority of delay reduction results from the elimination of one of the four traffic-signal phases at the intersections. This effectively adds more green time to the cycle for left-turning vehicles and reduces lost time associated with start-up delay and all-red phases. For the most effective operation, the two intersections should be controlled by coordinated signals.

The split configuration also eliminates and separates some conflict points relative to a conventional intersection. This, combined with the reduction in the number of signal phases, would be expected to demonstrate a net positive effect on safety.

The most significant disadvantages of split intersections are the high initial costs associated with construction and right-of-way acquisition, the likelihood of stopping at two intersections instead of one if the two signals are not well-coordinated and

possible wrong-way movements by unfamiliar drivers.[17,18] The effect of split intersections on pedestrians has not been well documented, but it does add an additional intersection to cross, which infers the likelihood of additional vehicle conflicts.

Split intersection designs are not common in the United States, although several conventional intersections in Israel have been converted to a split design since 1975 with overall positive effects. This design is considered to be most appropriate for use on isolated and congested suburban intersections with high left-turning volumes that are expected to experience traffic growth. This configuration is also regarded to be useful as a transition step to a grade-separated diamond interchange with an overpass on the through roadway.

5.3.6 Continuous Green T-Intersection

The continuous green T-intersection was developed specifically for three-approach T-intersections in which a minor collector roadway ends at a major roadway. In this configuration, illustrated in Figure 5–19, through traffic from one (or more) of the major street approach lanes flows continuously through the intersection while the median lane of this approach is used for left-turning traffic to the minor street. Left turns from the minor road are received by the departure side of the major street left-turn lane. For the most effective operation, it is recommended that the left-turn lane(s) be separated from the through lane(s) by an island or other channelizing feature to discourage potentially hazardous last-minute weaving maneuvers in and out of the turn lane.

In this configuration, movements between roadways are controlled by a two- or three-phase signal. A three-phase signal will be the most appropriate for heavier volumes because the major street left turns will be in conflict with the opposing major street through movements.

The obvious advantage to this design is the elimination of stops and reduced delay for through traffic in one direction of the major highway. The biggest disadvantage associated with continuous green T-intersections is its impact on pedestrians since the design does not permit protected crossings. Although it is not an inexpensive solution, the pedestrian crossing issue can be overcome with the installation of pedestrian bridges or tunnels. Other disadvantages compared to a traditional T-intersection include a lack of access to and from the properties adjacent to the continuous flow lane(s) and the increased potential for lane-changing conflicts prior to the initiation of the median through lane.

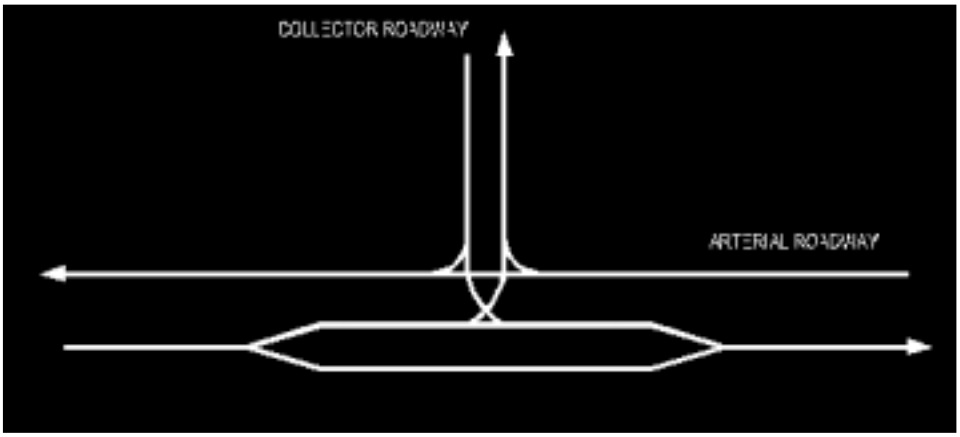


Figure 5–19: Continuous Green T-Intersection Diagram

Continuous green T-intersections are best suited for locations with high major street through volumes with low to moderate left-turn volumes from the minor street, and where no pedestrian crossings are expected. These intersections have been used by the Florida Department of Transportation with overall positive results.

5.3.7 Roundabouts

Modern roundabouts are circular intersections that incorporate channelized approaches, yield control and design geometry that facilitate moderate operating speeds.[7] Under the right conditions, a properly designed roundabout is thought to offer safety and efficiency benefits when compared to conventional intersections.[3]

A detailed discussion on the design and operational requirements and characteristics of roundabouts is included in Chapter 8 of this report and in the FHWA publication *Roundabouts: An Informational Guide*.[7]

5.3.8 Other Design Concepts

Numerous other unconventional design concepts have been conceived, but have yet to be implemented in the United States. These concepts include:

- Superstreet median intersection;
- Single-quadrant roadway intersection;
- Bowtie intersection; and
- Paired intersection.

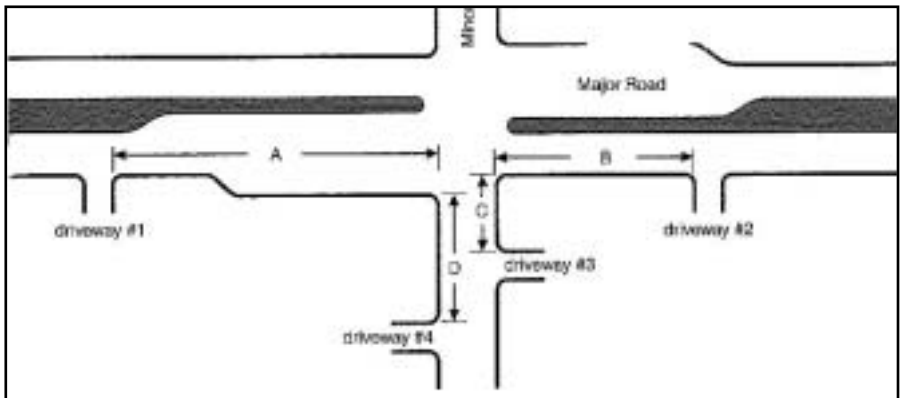
5.4 Access Control and Management

One of the key ingredients to safe and efficient intersection operation is the minimization of conflicting movements within a functional area. The preceding sections of this chapter presented ways in which this can be accomplished with the use of various geometric measures. Another effective means of minimizing conflicting movements at intersections is to control access to and from adjacent land developments in the vicinity of the intersection. The "systematic control of the location, spacing, design and operation of driveways, median openings, interchanges and street connections to a roadway" is known as *access management*.[10]

The purpose of access management is to "provide vehicular access to land development in a manner that preserves the safety and efficiency of the transportation system.[10] Available techniques include the use of median treatments, auxiliary lanes, common driveways (where multiple developments share a single access point to a roadway) and frontage roads that separate local and pass-through traffic into separate roadways. Access management techniques can be particularly beneficial at intersections because they can be used to control the location of merging, diverging and crossing traffic streams. A detailed discussion of access management planning, design and administrative issues can be found in the Transportation Research Board's (TRB) *Access Management Manual*.[10]

At intersections, the critical access management element is intersection corner clearance. Inadequate corner clearance at intersections, particularly those with high volumes, can result in diminished capacity and an increased number of conflicts. AASHTO advises against driveways being permitted within the functional intersection area.[1] Section 5.1.2 of this chapter defines and illustrates this concept of functional area.

To avoid these situations, the TRB report recommends the establishment of land use policies that require minimum corner clearance distances and the use of engineering studies to evaluate the impact of the traffic movements in the vicinity of a proposed driveway.[10] When these measures do not work, developers may be asked to construct access points at locations as far a possible from the intersection, use



Clearance Type	Sample Clearance Criteria
A = Upstream on the major roadway	Separation would equal or exceed the functional distance of the intersection $d_1 + d_2 + d_3$ in Figures 9-13 and 10-5. Sum the distances from Table 8-3 plus Table 10-2 plus queue storage.
B = Downstream on the major roadway	Separation would equal or exceed: 1) the upstream functional dimension of the driveway (sum of the distances from Tables 8-3 and 10-2), or 2) the influence distance (Table 9-8). Minimum separation is no less than the stopping distance (Table 9-5).
C = Approach side on the minor roadway	Queuing (Tables 9-12 and 9-13).
D = Departure side on the minor roadway	Separation of the intersection from entering and exiting maneuvers at the driveway (Figure 9-11)

1) Maneuver distances and methods for estimating queue storage are discussed in greater detail in the section on Auxiliary Lanes in Chapter 10, "Access Design."
2) The distance traveled during the perception-reaction time (Table 8-3) and maneuver distance (Table 10-2) for left turns and right turns will be the same. However, queue storage length may be quite different, with the left-turn queue storage being larger than that for right turns. Minimum corner clearance will be determined by the one (left turns or right turns) that has the largest maneuver plus queue storage distance.

Figure 5–20: Intersection Corner Clearance Dimensions
Source: 10. Figure 9–10, pg.157

directional right-in/right-out driveway designs and consider shared-access driveways with adjacent properties.

Figure 5–20 illustrates the location of the upstream and downstream clearances at a highway-to-highway intersection. Although not included here, readers are encouraged to review the *Access Management Manual*[10] for recommended distances.

5.5 Conclusion

Intersections are critical components of highway systems. By joining two or more directions of travel, the intersections significantly impact the operational efficiency of roadway networks. Thus, vehicles, pedestrians and bicycles are starting, stopping and changing lanes at intersections, creating high numbers of conflicts and the potential for collisions. A well-designed intersection must maximize the efficiency of all user movements, while minimizing the safety impacts on these users. It must also achieve both of these in a cost-effective manner. This is not an easy task.

This chapter highlights the design of the primary physical components of roadway intersections with an emphasis on both the operational and safety ramifications of various design treatments. The discussion is presented within the context of safety and efficiency for all user modes. In general, the design of intersections can be viewed as a sequential process that must first identify and define the users of the facility and their needs and expectations. This may include the need to adjust the importance of one or more design features, even to the exclusion of some potential users. Next is the analysis and development of the physical components of the intersections, such

as the alignments, cross section and control features. Each of these elements must be consistent with the type and number of users. The element must also be developed in accordance with the desires and expectations of the local community, including the need to provide safe and convenient access to adjacent properties and reduce adverse environmental impacts. Ultimately, the benefits of each consideration must be weighed against the costs, including the cost of construction, performance (travel time, delay, fuel consumption, emissions, etc.) and safety (property damage, injuries, etc.).

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chapter six

Traffic Control Devices

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6.1 Purpose of Traffic Control Devices

The purpose of traffic control devices "is to promote highway safety and efficiency by providing for the orderly movement of all road users on streets and highways throughout the nation."[1] Traffic control devices are the traffic engineer's method of communicating with the roadway user. The devices alert roadway users to rules and regulations applicable to a facility, warn the user of situations that may not be immediately apparent and guide the user toward his/her intended destination. These functions are provided in an effort to promote uniform and safe operation of roadway facilities.

To be effective, a traffic control device must satisfy the following five requirements:

1. Fulfill a need—if a device is not needed but installed anyway, it may be counterproductive to the goal of improving safety;
2. Command attention, or it will not be successful in conveying its meaning to the user, and thus the user will not be regulated, warned, or guided as anticipated;
3. Convey a clear and simple meaning, or the roadway users cannot be expected to respond properly;
4. Command respect from the roadway users, or users may ignore the device or even worse, develop a disrespect for similar devices in other locations, and
5. Give adequate time for an appropriate response, or an unsafe condition could result.

6.2 Federal and State Guidance

The Federal Highway Administration (FHWA) is responsible for producing, maintaining and updating criteria to promote the uniform application of traffic control devices on all streets and highways open to public travel in the United States. The standards for traffic control devices are contained in the Manual on Uniform Traffic Control Devices (MUTCD).*

Some recent additions to the MUTCD are specifically related to improving intersection safety, including:

- YIELD HERE TO PEDESTRIANS Signs (MUTCD Section 2B.11);
- In-Street Pedestrian Crossing Signs (MUTCD Section 2B.12);
- RIGHT TURN ON RED arrow (MUTCD Section 2B.45);
- U-TURN YIELD TO RIGHT TURN (MUTCD Section 2B.45);
- ONCOMING TRAFFIC HAS EXTENDED GREEN (MUTCD Section 2C.39); and
- New treatments for permissive green signals (MUTCD Section 4D.06).

Numerous other documents complement the MUTCD and provide useful information regarding the proper placement and use of traffic control devices. Commonly referenced documents include the following:

- *A Policy on Geometric Design of Highways and Streets*, 2001 Edition;[2]
- *Traffic Control Devices Handbook*, 2001 Edition;[3]
- *Standard Highway Signs*, 2002 Edition;[4]
- *Roadside Design Guide*, 2002 Edition;[7] and
- *Standard Specifications for Structural Supports for Highway Signs, Luminaires, and Traffic Signals*, 2001 Edition.[8]

In order to continue to receive highway funds from FHWA, each state must adopt a manual in conformance with the MUTCD. Many states simply adopt the MUTCD as a whole, while others adopt the MUTCD with certain amendments that are specific to that state. A few states do produce an entire manual of their own, but they typically are very much like the MUTCD.

In areas where the MUTCD allows for multiple options or provides only general guidelines, some states create different standards that they believe best embodies the intent of the MUTCD. Additionally, there are often local preferences to how traffic control devices should be placed or what devices should be used. For example, some warning signs in the MUTCD allow either word or symbol messages. Some local areas have a preference for word messages while others prefer symbol messages.

6.3 Design and Placement of Traffic Control Devices

6.3.1 Uniformity

The MUTCD provides a great deal of detail on the proper design and placement of traffic control devices. The MUTCD is founded on the concept of uniform application of traffic control devices so that road users understand the meaning of the device and know what response is expected from them. This requires that the correct device be placed in the proper location so that the intended audience (for example, a motorist) has sufficient time to see, process, understand and perform whatever action is required.

6.3.2 Warrants

Many of the traffic control devices described in the MUTCD have accompanying conditions (commonly referred to as warrants) that help the engineer determine whether that device may be the appropriate device for a particular situation. The installation of a device that is not warranted may lead

* The MUTCD is formally adopted by FHWA and is developed with assistance from more than 200 volunteer members of the National Committee on Uniform Traffic Control Devices. FHWA intends to maintain the most current version of the MUTCD on its Web site (mutcd.fhwa.dot.gov). The reader is reminded that a thorough discussion of the detailed and specific requirements of all types of traffic control devices and their proper application is beyond the scope of this report. The reader is thus referred to the MUTCD where more detail is required.

to an inappropriate response by roadway users. For example, in locations where unwarranted all-way stop-controlled intersections are installed to control speeding in residential areas, typical compliance with the STOP sign is poor (for example, drivers not coming to a complete stop). Drivers tend to increase their speeds in roadway segments between intersections to make up for the delay at an unwarranted stop. It is therefore important that only properly warranted traffic control devices be installed at an intersection.

A discussion of the proper application of traffic signal warrants is presented in Section 7.1.3 of Chapter 7. That material refers to all traffic control device warrants.

6.3.3 Flexibility

The MUTCD should be used as a set of guiding principles and not a set of rigid rules. It permits considerable flexibility in the application of traffic control devices to promote intersection safety.

Many of the standards contained in the MUTCD represent minimums. In some instances, it may be appropriate to provide more than the minimum level of traffic control device use at an intersection to ensure the desired level of intersection safety.

The MUTCD also allows for experimentation with new proposed traffic control devices. Some of the added devices mentioned in Section 6.2 have been through the experimentation process and have proven to be effective traffic control devices for improving safety. If an experimental device or unique application is tried at an intersection, it is imperative that a follow-up evaluation be performed to ascertain whether or not the new installation succeeded in improving intersection operations and safety.

6.3.4 Professional Judgment

Even a document as thorough and comprehensive as the MUTCD cannot possibly cover all of the different situations and scenarios that may be encountered when considering the installation of traffic control devices. It is always up to the professional judgment of the responsible engineer to determine whether a particular device is necessary. To that end, it is important to emphasize that a warrant is not a mandate. Even though conditions at a certain location may satisfy one or more of the warrants for the installation of a particular device, other factors may preclude the use of that device. It is essential that all decisions regarding the choice and installation of traffic control devices be based on the application of modern engineering information and principles and not on the blind application of a “standard.”

As a part of the engineering study required before the placement of any traffic control device, a thorough field review is essential. In many instances, conditions exist in the field that are not readily discernable from a set of roadway design plans or even photographs. There may be sight distance obstructions, geometric design considerations, topographic features, or other concerns that might affect the traffic control device proposed or necessitate the installation of additional traffic control devices.

6.4 Types of Traffic Control Devices

The following sections give brief descriptions of the various types of traffic control devices and some notes about their use. At the end of each section, a listing of specific example applications or enhancements to that type of traffic control device is shown. For many of these applications, crash reduction factors are shown. The reader should exercise caution when using these data.

The text primarily addresses issues related to motor vehicle safety. This chapter should be read in conjunction with Chapter 4 in order to receive a complete picture of geometric design issues affecting all users of an intersection.

Numerous photographs are included in this chapter to illustrate concepts, not design details. Application of these concepts requires adherence to all federal and local design standards.

6.4.1 Signs

6.4.1.1 Types of Signs

Traffic signs are typically divided into three categories: regulatory, warning and guide signs.

- **Regulatory Signs:** Regulatory signs give notice of traffic laws and regulations and are typically rectangular-shaped with the larger dimension vertical. Many regulatory signs, especially those that contain word messages, are comprised of a black legend and border on a white background. Some notable exceptions to this format are the STOP, YIELD, DO NOT ENTER and WRONG WAY signs. Some regulatory signs feature a red circle and slash, the universal symbol for "prohibited," over a particular type of movement or vehicle type to indicate a prohibition against that movement or vehicle class. Regulatory signs are backed by state statute and/or local ordinance and are enforceable by a written citation. Some typical regulatory signs are shown in Figure 6–1.

- **Warning Signs:** Warning signs alert the roadway user of conditions that may not be readily apparent or unexpected. Warning signs associated with a permanent hazard are black and yellow, while those that indicate temporary hazards related to road construction (work zones) are black and orange. The color for warning signs that indicate the potential presence of un-protected roadway users (for example, pedestrians, school children, bicyclists) on or near the travel lanes is fluorescent yellow-green and black. Some typical warning signs are shown in Figure 6–2.

- **Guide Signs:** Guide signs assist the roadway user by providing identification of intersecting routes

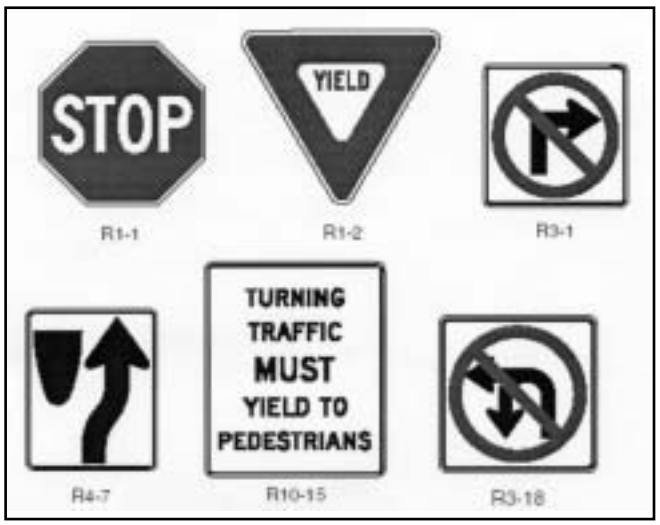

Figure 6–1: Typical Regulatory Signs
Source: 1

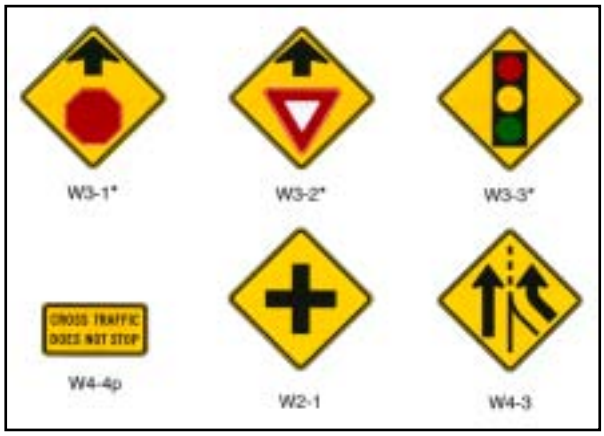

Figure 6–2: Typical Warning Signs
Source: 1

(for example, street name and advance street name signs); pointing the direction to cities, towns, villages, or other destinations; advising the distance to destinations; identifying landmarks; and other information to help users navigate toward their destination in an efficient manner. Guide signs are typically rectangular signs with the larger dimension horizontal. Guide signs providing route and directional guidance information are white and green; guide signs providing information on the location of recreational or cultural areas of interest are brown and white. Some typical guide signs are shown in Figure 6–3.

Also included in the guide sign category are route markers and general service signs. For an intersection that is located close but perhaps not adjacent to a hospital, tourist information center, campground, general services (such as gas, food and lodging), or other significant traffic generators, the use of guide signs may improve the safety of the intersection by providing the motorist advance notification of the presence and direction to these services.

6.4.1.2 Sign Placement and Sign Supports

A critical aspect to the use of signs is proper placement. In order to function effectively, the sign must be positioned along the roadway to maximize the probability that the driver can and will see it in sufficient time to initiate and safely complete any required action.

Also important is the use of proper sign supports. To avoid unnecessary injury to vehicle occupants, it is vital that sign posts break away or yield when hit by

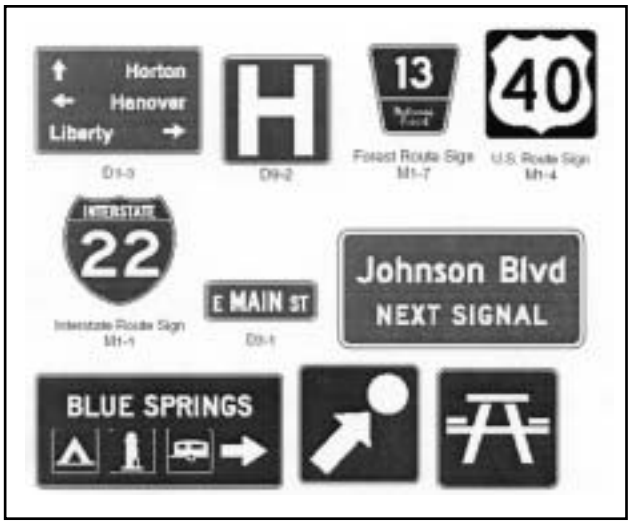

Figure 6–3: Typical Guide Signs
Source: 1

an errant vehicle that has left the roadway. Figure 6–4 shows a sign location where the sign supports properly yielded when struck. Drilled wooden posts, slip bases, U-channels and perforated tube supports are some of the common mounting devices used for highway signs. Figure 6–5 shows a close-up view of a slip base mounting used for an advance street name sign. For improved intersection safety, the sign supports should be omni-directional (i.e., they will break away when struck from any direction). This is particularly vital at intersections, where vehicles may hit the sign from any direction.

Figure 6–4: Signs Knocked Down by Errant Vehicles

Figure 6–5: Slip Base Sign Post Mounting

6.4.1.3 Sign Content

Sign messages should be short and convey a clear, simple and unambiguous message to intersection users. The MUTCD does allow sign messages to be altered to accommodate local conditions, but there are limits on how much a sign may be modified and still be considered compliant with the manual.

6.4.1.4 Nighttime Visibility of Signs

The MUTCD requires that signs be retroreflective or illuminated. The term "retroreflective" refers to the ability of a sign to take the incident light provided by the vehicle headlights and reflect it back towards the driver. Current signing practices use sheeting materials optically engineered to be highly efficient retroreflectors and specifically designed for the nighttime driving environment. As a result, the entirety of the sign (legend, background and border) lights up for the driver when illuminated by the vehicle's headlights. (The exception to this is a sign with black legends that do not retroreflect.) This has greatly increased the nighttime visibility of roadway signs and has led to increased safety. Signs are normally mounted just off perpendicular (about 5 degrees toward the shoulder) to the direction of traffic in order to eliminate specular glare. Signs that are 30 ft. or more from the edge of pavement should be turned slightly in towards the approaching traffic.

6.4.1.5 Changeable Message Signs

Many types of signs are used at intersections to display messages at different times. These are referred to as changeable message signs. Some intersections feature blank-out signs that are blank most of the time, but illuminate to display a particular message during certain periods of the day. Other signs either fold out mechanically to display a message or remain closed, showing no message during other periods. Another type of changeable message sign is commonly referred to as a dynamic message sign (DMS) because the sign is capable of displaying virtually any message that the operator desires. The sign is therefore not limited to just one or two total messages. The DMS technology has been used for many years in freeway management applications to alert motorists of incidents or congestion ahead. DMS applications are now also used on arterial streets to display messages regarding congestion or incidents. These dynamic message signs are designed to provide time, site and traffic-relevant information to the driver in real-time.

6.4.1.6 Specific Applications to Enhance Intersection Safety

Some of the more common treatments used with traffic signs to promote intersection safety include the following:

- Overhead street name signs—Motorists in the inside lanes of a multi-lane approach may have their view of a ground-mounted street name sign located on the street corner blocked by traffic in the outside lanes. Placement of the street name sign overhead near the traffic signal indications (Figure 6–6) significantly improves visibility from all lanes of the intersection approach.
- Overhead guide signing—Provision of guide sign information over the lanes can encourage motorists to move into the proper lane in advance of the intersection (Figure 6–7). This will help to reduce the frequency of sudden lane changes at the intersection and can be expected to reduce some types of intersection crashes.
- Internal illumination—The previous two treatments seek to improve intersection safety by improving the conspicuity of the sign messages by placing them overhead. To further improve the nighttime performance of these signs, it may be beneficial to also improve their visibility through internal illumination. Many jurisdictions are now using internally illuminated overhead street name signs (Figures 6–8 and 6–9) and intersection regulatory signs (for example, turn prohibitions). Because these signs are mounted overhead (in other words, higher than the low beam focus of the vehicle headlights), there may not be enough light from the headlights for the nighttime

Figure 6–6: Overhead Street Name Sign

Figure 6–8: Internally Illuminated Street Name Sign in Daytime

Figure 6–7: Overhead Guide Signs on an Intersection Approach

Source: Scott Wainright

Figure 6–9: Internally Illuminated Street Name Sign in Nighttime

Source: Scott Wainright

motorist to adequately see these signs. This is especially true in low-visibility conditions such as rain or fog. The use of internal illumination greatly enhances the nighttime visibility of intersection signing. The MUTCD offers the following guidance on illumination of overhead signing: "All overhead sign installations should be illuminated unless an engineering study shows that retroreflection will perform effectively without illumination."

- Advance street name signs—The use of advance street name signs helps the motorist to move into the proper lane prior to arriving at an intersection. This treatment can be expected to reduce erratic behavior at intersections. Figure 6–10 shows a typical advance street name sign. The sign in Figure 6–11 shows a sign where the street to the left has a different name than the street to the right of an intersection.
- Advance intersection warning signs—Advance warning signs for intersections (Figure 6–12) have shown crash reduction factors of 30 percent in rural locations and 40 percent in urban locations.[5] Section 7.4.2 of Chapter 7 provides guidance on the application of active advance warning signs.
- Oversized signs—In many cases it may be appropriate to use sign sizes larger than the minimum specified in the MUTCD. The use of larger signs can have significant benefits in improving intersection safety with a crash reduction factor of 20 percent, particularly in areas where there may be large concentrations of elderly road users or unfamiliar drivers.[5]
- Improved retroreflectivity—The nighttime visibility of traffic signs can be greatly improved by the use of a higher standard of retroreflective sheeting (for example, from super engineer grade

Figure 6–10: Advance Street Name Sign

Figure 6–12: Advance Intersection Warning Sign

Figure 6–11: Advance Street Name Sign with Two Names

to high intensity grade). Often there are many visual distractions at intersections and the important traffic control devices must compete for motorists' attention. By increasing the retroreflectivity of the signing, the important traffic control devices stand out better against the background visual clutter that may be present at properties adjacent to the intersection.

- Double indication—At multi-lane intersection approaches, motorists in a particular lane may have their visibility of a sign blocked by traffic in an adjacent lane. Therefore, it may be beneficial to install the sign on both sides of the approaching roadway. Studies have shown that a crash reduction factor of between 30 and 40 percent can be realized from double-signing warning signs in some locations.[5]

6.4.2 Pavement Markings

6.4.2.1 Types of Markings

At an intersection, lane lines, STOP lines, crosswalk markings and word and symbol messages are all used in combination to delineate the proper places for vehicles and pedestrians. A typical intersection layout is shown in Figure 6–13.

- Longitudinal lines are provided for most roadways to delineate individual lanes and assist motorists in staying in their own lane. Longitudinal lines consist of the following primary colors:
  - Yellow lines, which separate traffic traveling in opposite directions or delineate the left edge of pavement for a divided highway, one-way street, or ramp; and
  - White lines, which separate traffic lanes that are traveling in the same direction or delineate the right edge of pavement.

  Longitudinal lines are solid, broken, or dotted, depending on the specific application and the intended message or regulation that is to be communicated to drivers.

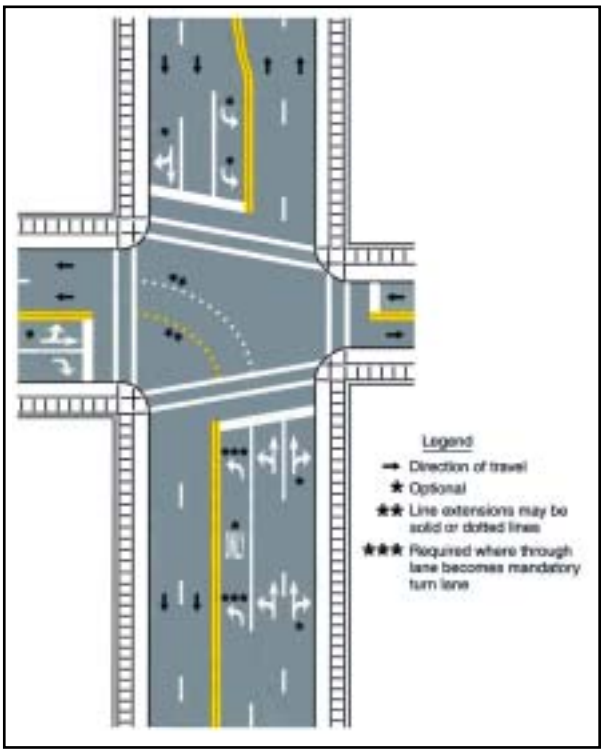

Figure 6–13: Typical Pavement Markings at an Intersection
Source: 1

- STOP lines are provided at signalized intersections and at stop-controlled intersections to clearly indicate to the motorist the point at which they are expected to stop. The stop line consists of a single white solid line that is 12- to 24-in. wide.
- YIELD lines are composed of isosceles triangles pointing toward the approaching vehicles. The reader is referred to Section 3B.16 of the MUTCD for more details on the specifics of stop and yield markings.
- Crosswalk markings are used to provide guidance to pedestrians by indicating the path that they should take when crossing the roadway. Figure 6–14 shows a crosswalk and adjacent speed humps used to slow vehicular traffic approaching the crosswalk. Figure 6–15 shows a crosswalk that is supplemented with an in-street pedestrian

crossing sign. Crosswalk markings consist of solid white markings that may be between 6 and 24 in. in width. There are many configurations of crosswalk markings that are currently being used. The reader is referred to Chapter 4 and Section 3B.17 of the MUTCD for more details on the specifics of crosswalk markings.

- Words and symbols may be used to supplement pavement markings and signs to provide clear direction to the motorist. Some typical word messages are STOP, R X R and SCHOOL. Pavement arrows are also commonly used to delineate lane use. The word ONLY may be used to supplement exclusive turn lanes. The reader is referred to Section 3B.19 of the MUTCD for more details on the specifics of word and symbol markings.

6.4.2.2 Object Markers and Delineators

Object markers and delineators are another type of traffic control device grouped with pavement markings. Object markers typically highlight obstructions in the roadway environment. Delineators are used to supplement pavement markings and are required to be the same color as the line that they represent. Delineators are sometimes used in painted islands and in median areas to provide a deterrent to vehicles that might otherwise traverse the area.

6.4.2.3 Materials for Pavement Markings

Current pavement marking systems include a wide variety of materials and constructions. The most commonly used are waterborne paint, thermoplastic, epoxy and tapes. Retroreflective glass beads or optical elements are incorporated in the construction to provide nighttime visibility of the marking. Conventional paint markings are significantly less expensive than other materials, such as thermoplastic and tape, but paint is also significantly less durable. Paint typically needs to be re-applied every year, whereas the durable materials can provide between 3 and 5 years of service.

An important consideration in pavement markings is the skid resistance of the marking. Of particular concern are intersections where wide longitudinal thermoplastic lines are used for crosswalks. In these cases, the skid resistance of the thermoplastic stripe, particularly after it has aged a couple of years and when wet, is significantly lower than that of the roadway surface. These large slick areas are known to be a concern for pedestrians, motorcyclists and bicyclists.

Figure 6–14: Crosswalk and Speed Hump Markings

Figure 6–15: In-Street Pedestrian Crossing Sign

In some locations, ceramic buttons are used in lieu of thermoplastic or paint. The ceramic buttons provide good visibility even when the road is wet and tactile feedback to motorists who are drifting out of their lanes. Raised reflective pavement markings (RPMs) are sometimes used to supplement the markings. Particularly in areas that are subject to significant rainfall on a regular basis, the use of RPMs greatly enhances the visibility of the lane lines in wet weather conditions. Special plow-resistant RPMs are available for installation in areas that are subject to snowfall.

6.4.2.4 Specific Applications to Enhance Intersection Safety

Some common enhancements to pavement markings that may be applied to increase intersection safety include the following:

- Wider lines—Increased width of longitudinal lines has been very effective in promoting positive guidance, particularly among elderly motorists.[6]
- Increased use of raised reflective pavement markings—These devices greatly increase the visibility of the pavement markings at night and in low-light conditions. They are particularly beneficial in wet-pavement situations where the retroreflectivity of normal markings is reduced due to the reflectivity of the water on the roadway.
- Increased brightness of pavement markings—The use of improved glass beads can increase the retroreflectivity of standard pavement markings.
- "Horizontal signing"—The use of additional pavement messages can help motorists get into the proper lane in advance of the intersection (Figure 6–16).
- Add left-turn lanes—For rural intersections, striping a left-turn lane on existing pavement can result in a crash reduction factor of 44 percent.[5]

Figure 6–16: Horizontal Signing on Intersection Approach
Source: Scott Wainright

6.4.3 Traffic Signals

Chapter 7 covers traffic signal design and operations in depth. The remainder of this section discusses an atypical form of signal displays (beacons) and presents a summary of potential safety benefits associated with various traffic signal improvements.

6.4.3.1 Beacons

Intersection control beacons are used at intersections that require more emphasis than can be achieved with standard signs alone. Intersection beacons are frequently used at low volume intersections that have high-speed traffic and a significant crash history. Flashing beacons indicate to the motorist the need for additional caution at the intersection. Typical applications include the use of flashing-yellow/flashing-red beacons at two-way stop intersections and all-way flashing red beacons at all-way stop intersections.

For these applications, the flashing red beacon supplements a standard STOP sign and the flashing yellow beacon cautions drivers on the major street that this intersection merits increased awareness. At intersections with the flashing yellow/flashing red operation, motorists on the stop condition approaches

may mistakenly believe they are approaching an all-way stop intersection, which can lead to right-angle collisions. At intersections that are experiencing these types of collisions, a supplemental CROSS TRAFFIC DOES NOT STOP plaque (W4-4p) may be installed below the STOP sign to alert approaching motorists of this condition.

Other types of beacons include warning, speed limit and stop beacons.

- Warning beacons are used to provide supplemental emphasis to warning signs, bring attention to obstructions in or immediately adjacent to the roadway, emphasize midblock crosswalks and emphasize some regulatory signs. The warning beacon is made up of one or more signal faces with a flashing circular yellow signal display.
- The speed limit beacon is a similar flashing circular yellow display used to supplement and emphasize the speed limit sign.
- Stop beacons are used in conjunction with a standard STOP sign. The signal indications for a stop beacon are flashing circular red. If two indications are used and they are mounted horizontally, the MUTCD requires that they flash simultaneously to avoid being confused with a highway-rail grade crossing. If two signals are used and they are mounted vertically, they must flash alternately.

6.4.3.2 Specific Applications to Enhance Intersection Safety

Some possible enhancements to traffic control signals that may be applied to improve intersection safety include the following. The reader is also referred to Chapter 7 for additional discussion of the safety and mobility implications of traffic signals.

- Protected left turns—Some studies indicate a crash reduction factor of greater than 90 percent after a change is made from permissive to protected-only left turns.[5]
- Install pedestrian countdown indications—Where these have been used, the number of pedestrians that are still in the crosswalk at the onset of a conflicting green phase has been dramatically reduced.[5]
- Coordinate adjacent signals—Studies show a total crash reduction of up to 25 percent in the peak hours where previously uncoordinated signals have been coordinated.[5]
- Change late-night flashing yellow/red operation to all-night normal signal operation—Recent studies have indicated that intersection safety can be greatly improved by having the traffic signals remain in full-color operation throughout the night. Crash reduction factors of 78 percent for right-angle crashes and 32 percent for all crashes during the period of night operation have been reported.[5]
- Use red "T" signal heads—These heads feature two circular red indications side-by-side at the top of the signal head to emphasize the red indication (Figure 6–17). In some studies they have resulted in a 35 percent reduction in red-light running crashes.[5]

Figure 6–17: Red "T" Signal Heads
Source: Scott Wainright

- Use 12-in., rather than 8-in., signal indications—The use of 12-in. heads has been shown to cut intersection crashes nearly in half.[5]
- Provide additional signal heads—By providing a signal head for each lane on a multi-lane approach, a crash reduction factor of 48 percent for right-angle crashes and 22 percent for all crashes may be realized.[5] This treatment is especially effective if combined with clear lane-use signing (Figure 6–18).

- BE PREPARED TO STOP signs—At signals that are located on the downhill side of a vertical curve, it may be useful to indicate to approaching motorists that they are approaching a signal and, when appropriate, that the signal indication is red. The use of these signs, supplemented with a warning beacon wired to the traffic signal cabinet has resulted in a decrease of more than 70 percent in fatal and injury crashes and total crash reduction factors of 30 percent in rural locations and 40 percent in urban locations.[5]

- Provide median refuge for pedestrians—At large intersections with wide medians, it may be beneficial to provide pedestrian refuge areas where the crossings can be performed in two stages. In these situations, it is important to include pedestrian detectors in the island so that pedestrians will not be stranded in the median without a way to safely complete their crossing. Figure 6–19 shows a pedestrian crossing with a wide median refuge area. Figure 6–20 shows the push button installation within the median refuge area. A similar application is shown previously in Figure 4–21.[5]

Figure 6–18: Signal Head Per Lane with Clear Lane Use Signs
Source: Fred Ranck

Figure 6–19: Crosswalk with Wide Median Refuge Area

Figure 6–20: Pedestrian Pushbutton in Median Refuge Area

- Temporary turn prohibitions—This treatment has been used at some school signal crossings as a means to provide better protection for school children. The exclusive pedestrian phase is called by the school crossing guard and the signal controller activates the turn prohibitions when the exclusive pedestrian phase starts. This application could use an overhead sign that illuminates to indicate, for example, NO TURN ON RED or NO RIGHT TURN just during the exclusive pedestrian phase.

6.5 Intersections with Unique Requirements

6.5.1 School Areas

A school area typically has a great deal of pedestrian activity, as well as congestion caused by (1) parent pick-up or drop-off activities and (2) the ingress and egress of school buses. The MUTCD states: "the type(s) of school area traffic control devices used, either warning or regulatory, should be related to the volume and speed of vehicular traffic, street width and the number and age of the students using the crossing" (MUTCD Section 7A.01). Thus it is desirable to create traffic control treatments that fit the nature of the particular school location. However, for simplicity and uniform application, many jurisdictions have developed standard treatments for all school areas, including a reduced speed school zone. This reduction is a local decision, or in some cases may be based on a state's vehicle code requirements, and is not mandated by the MUTCD.

When implemented, reduced speed limits in school zones do tend to promote an increase in safety and help to make drivers more conscious of the presence of pedestrians. For maximum benefit, experience has shown that the reduced speed areas should be kept as short as possible. Drivers tend to comply with the reduced speed limits in school zones, but if the reduced speed zone extends for too great a distance, drivers lose respect for and increasingly violate the reduced speed limit.

6.5.2 Highway-Rail Grade Crossings

Although the frequency of crashes at highway-rail grade crossings is lower than at other intersection types, these crashes are typically more catastrophic. Numerous factors should be considered for deciding the appropriate traffic control for a grade crossing, including the following:

- Train frequency;
- Train speed;
- Vehicular traffic volume;
- Vehicular traffic speed;
- Sight distance for vehicles; and
- Crash history.

For crossings with low traffic volumes, only a crossbuck and grade crossing advance warning sign are typically used. As traffic volumes increase, the level of traffic control at these crossings typically increases accordingly with warning lights, gates, etc. At many crossings where trains travel at high speeds, a higher level of traffic control is justified to improve the safety of the crossing regardless of the vehicular traffic volume. Highway-rail grade crossings are covered in MUTCD Part 8.

For highway-rail grade crossings within 200 ft. of a signalized intersection, the railroad crossing warning system (which controls the lights and gates) is required to be interconnected to the signalized intersection traffic controller. At other intersections where the distance may be greater than 200 ft., but where the queue from the traffic signal may encroach upon the railroad crossing, interconnection should be considered. When a train approaches the crossing, the signalized intersection controller initiates a special signal sequence that preempts normal signal programming. This preempt is typically made up of a track clearance phase and a dwell phase. The track clearance phase is critical for the intersection approach that crosses the track. If the signal for that approach had been red prior to the preempt call, there is a possibility that vehicles are queued across the tracks. Therefore, the track clearance phase must have sufficient time prior to the arrival of the train to

safely clear the queue through the intersection. Once the train arrives at the crossing, the movement that crosses the tracks is unable to move because it is impeded by the train. Therefore, the signal controller will typically dwell in the green for the approaches that parallel the track. This allows the movements that do not conflict with the train to continue. Once the train has cleared the area, the preempt ends and the signal may return to normal operation.

In some urban areas, the safety of light rail transit grade crossings is a concern. Light rail transit alignments may be grouped into one of the following three types:

- Exclusive—where the transit vehicle has an exclusive right-of-way that prohibits use by vehicles or pedestrians;
- Semi-exclusive—where the transit vehicle has a separate right-of-way, but vehicles and pedestrians may share the use of this right-of-way at certain crossings or other locations; and
- Mixed-use—where the transit vehicle shares the right-of-way with all types of road users.

Mixed-use and semi-exclusive operations present special challenges for safe intersection control. Many agencies are using blank-out signs at these intersections to prohibit vehicles from crossing the tracks when a light rail transit vehicle is approaching. Special traffic signal indications may also be used for transit vehicles, which may require the use of transit only signal phases. For additional details, traffic control for light rail transit is covered in MUTCD Part 10.

6.6 Maintenance of Traffic Control Devices

It is good practice to implement a comprehensive traffic control device maintenance program to ensure that the devices are maintained at an adequate level to meet the needs of all users of the intersection. The program should include both periodic programmed maintenance and unscheduled "emergency" maintenance activities.

6.6.1 Signs

Issues to consider regarding highway signs include the following:

- The retroreflective sheeting used on sign faces has a certain useful life. After a few years of weathering, signs begin to lose their retroreflectivity. A sign that appears adequate in the daytime may be nearly invisible at night if the retroreflectivity of the sheeting has diminished.
- Signs may be exposed to a lot of dust and dirt. If the dust and dirt clings to the sign, nighttime visibility of the sign may be severely reduced. A periodic program of washing the signs may help to keep the nighttime visibility high.
- Another common problem is vegetation that may grow and obstruct the visibility of a sign. For sign locations with nearby vegetation, a planned program of trimming may be required.
- Signs may get damaged either by vandals or vehicles. Agencies must have the appropriate materials and personnel to quickly respond to and replace downed signs to minimize the exposure to what may be an unsafe condition caused by the absence of a particular sign.
- Another problem that many agencies have to deal with is graffiti on signs. Some of the commercially available graffiti removers adversely affect the retroreflectivity of the sign sheeting material. Some agencies have found it more efficient to replace the signs rather than try to clean them.

6.6.2 Signals

Traffic signals have several unique maintenance issues that must be considered.

- The initial signal timing plans that are installed when the signal is turned on are based on traffic

count information compiled prior to the installation of the signal. Once the signal has been installed, the traffic patterns around the intersection may change due to the presence of the new device.

- Additionally, traffic patterns around an intersection will change over time due to new development, changes in land use, other demographic changes, etc. This requires a continual program of traffic signal retiming throughout the life of the traffic signal.
- If modifications are made to the intersection (no matter how slight) or changes made to the approaching roadway that might affect operating speeds, the clearance times may need to be reevaluated.
- Throughout the life of the signal there will also be occasions where an indication will burn out or lose intensity, detectors fail, controllers malfunction, or errant vehicles damage the controller cabinet. Agencies must have spare parts and equipment and adequate "on-call" personnel to respond quickly to these types of events. Many agencies have found that the frequency of these "emergency" maintenance needs can be greatly reduced by a well-established program of periodic maintenance. By performing controller cabinet inspections and maintenance at each intersection and re-lamping signals before they burn out, the number of emergency calls can be significantly reduced. Some newer technologies such as LED traffic signals are expected to reduce the frequency of periodic maintenance.

6.6.3 Markings

Markings will also require a program of periodic maintenance.

- During a period of time, markings will lose retroreflectivity or get worn out by traffic traveling over them. Markings are also subject to unscheduled maintenance in the event of spilled loads (concrete, paint, solvents, etc.) that may cover or destroy them.

Many agencies maintain an inventory of their traffic control devices to help in the planning and scheduling of periodic maintenance activities. This inventory can predict when a device may need to be replaced. A good inventory can also help in the recovery from large-scale natural disasters. In the event of a major hurricane, for example, many traffic signs may be blown away by high winds. With the aid of a complete, detailed inventory of what signs were installed in what locations, the responsible agency can move quickly to return conditions to how they were prior to the event.

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chapter seven

Traffic Signal Operations

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7.1 The Basics of Traffic Signal Control

This chapter presents the concepts underlying traffic signal control and documents potential safety and efficiency benefits and drawbacks for various traffic signal control measures. A complete discussion of traffic control devices (including limited material on traffic signals) is presented in Chapter 6.

Numerous studies are cited in this chapter regarding the effect of signal installation, design and operation of intersection safety. The reader is cautioned that no attempt has been made to ascertain the validity or statistical integrity of these studies. However, the studies are useful for indicating general trends and serving as anecdotal evidence of the effect on intersection crashes that may be expected when traffic signals are installed or modified.

Numerous photographs are included in this chapter to illustrate concepts, not design details. Application of these concepts requires adherence to all federal and local design standards.

7.1.1 Objectives

The overall objective of signal control is to provide for safe and efficient traffic flow for all intersection users, along routes and in street networks. Traffic control signals are valuable devices for the control of vehicle and pedestrian traffic and must be designed and operated considering the needs, capabilities and limitations of all users.

If traffic signals are justified, properly located and maintained, the following benefits may be achieved:

- Reduce the frequency of certain types of crashes, especially right angle and pedestrian crashes;
- Improve the traffic-handling capacity of the intersection;
- Interrupt heavy traffic at intervals to permit other traffic (motor vehicles, bicycles and pedestrians) to cross;

- Reduce the delay to vehicular and pedestrian traffic using the intersection; and
- Provide for the continuous, or nearly continuous, movement of traffic at a designated speed along a given route when coordinated with control devices at other intersections.

7.1.2 Crash Patterns Related To Signalization

The installation of traffic control signals can be an effective means to reduce the severity and frequency of crashes at intersections. However, traffic control signals will not solve all types of intersection crash problems. A recent study in Iowa[11] yielded the changes in crash rates shown in Table 7–1 when new traffic signals were installed or existing signals were modified. As can be surmised from the data in Table 7–1, the effect of signal installation on crashes varies depending on signal phasing and intersection geometrics.

Similarly, a study of 67 new signal installations in Michigan[13] found a 15 percent net reduction in total crashes, 7 percent reduction in injury crashes, 52 percent reduction in right-angle crashes and 32 percent reduction in "other" crashes. Left-turn crashes increased by 75 percent (presumably, these signals did not provide protected left-turn phases) and rear-end crashes increased by 64 percent.

In summary, a traffic control signal, if properly designed and operated, can reduce the frequency and severity of the following types of crashes:

- Crashes involving substantially right-angle collisions or conflicts, such as between vehicles on intersecting streets;
- Crashes involving conflicts between straight moving vehicles and crossing pedestrians;
- Crashes involving left-turning vehicles and opposing straight through or right-turning vehicles if a protected left-turn phase is provided; and
- Crashes involving excessive speed if signal coordination will encourage slower speeds on the main street.

Table 7–1: Percent Crash Reduction After Signal Installation or Modification in Iowa

Crash Type	New Signal (%)	New Signal and Left-Turn Lanes (%)	Add Protected Left-Turn Phase to Existing Signal (%)	Add Protected Left-Turn Phase and Left-Turn Lane to Existing Signal (%)
Right-Angle	61	63	30	52
Rear-End	(-28)	(-44)	0	37
Left-Turn	(-27)	35	51	73
Other	(-9)	17	(-60)	45
Total	(-4)	20	36	58
Major Injury	43	87	22	85
Minor Injury	8	49	50	65

Notes: A positive value indicates a reduction in crashes.
A negative value indicates an increase in crashes.
Source: Adapted from 11

Traffic control signals should not be expected to reduce the following types of crashes:

- Rear-end collisions, which often increase after signalization;
- Crashes involving left-turning vehicles and opposing vehicles if a protected left-turn phase is not provided;
- Crashes involving turns made from the wrong lane; and
- Collisions between turning vehicles and pedestrians when both movements are made during the same interval.

7.1.3 Criteria for Installing Traffic Signal Control

Traffic signals should not be installed unless one or more of the signal warrants in the *Manual on Uniform Traffic Control Devices* (MUTCD) are met. The MUTCD warrants are as follows (although some agencies do not use all of these warrants):

- Warrant 1: 8-Hour Vehicular Volume
- Warrant 2: 4-Hour Vehicular Volume
- Warrant 3: Peak Hour Volume
- Warrant 4: Pedestrian Volume
- Warrant 5: School Crossing
- Warrant 6: Coordinated Signal System
- Warrant 7: Crash Experience
- Warrant 8: Roadway Network

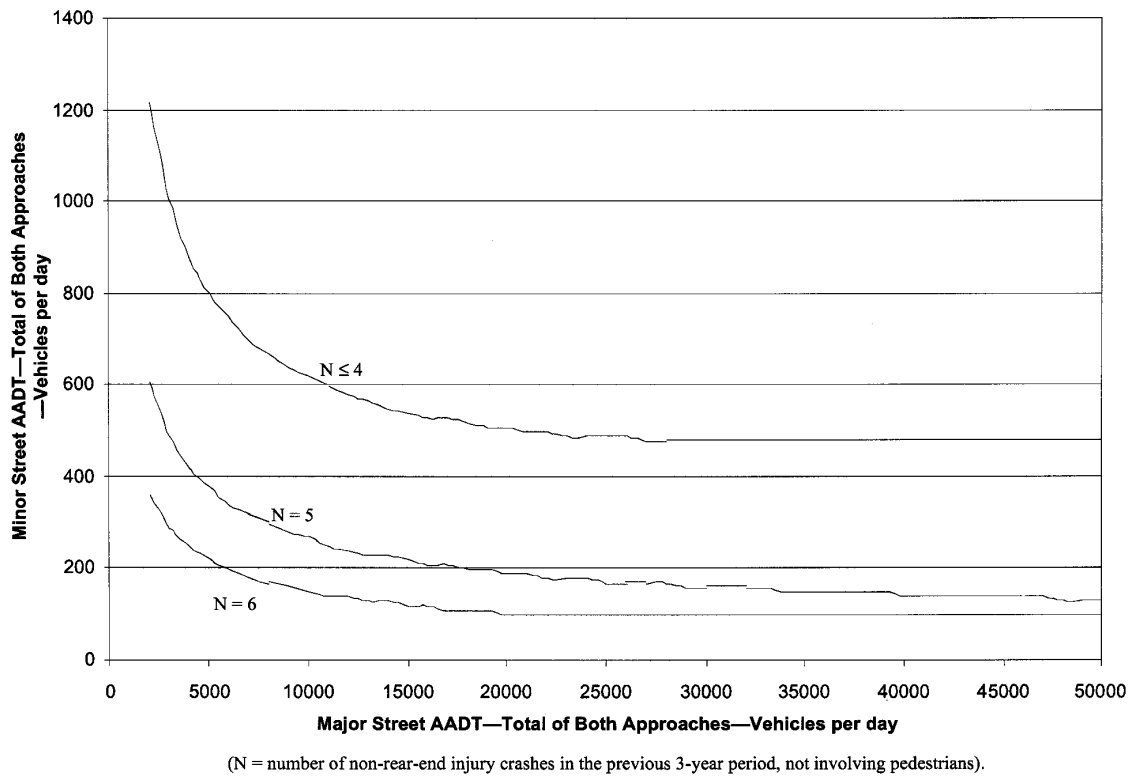

Figure 7–1: Potential New Warrant for Signal Installation (Four-Leg Intersection)
Source: 34

The warrant for signal installation based on crash experience (Warrant 7) is currently being evaluated for possible revision. A recent research project[34] recommended a revised warrant based on an analysis of the net change in crash frequency and severity that would be expected if a signal were installed. Figure 7–1 is one of the warrant charts recommended by this study. If the plotted point determined by the major and minor street volumes is less than the threshold values for "N" (the number of non-rear-end injury and fatal crashes during the previous 3 years), then it can be assumed that there will be a safety reduction if traffic signals are installed. If the plotted point falls above the threshold values for "N," the report recommends that a detailed safety analysis be prepared, comparing the benefits of crashes forestalled with the direct and indirect costs of signalization.

When a traffic signal is warranted, it is presumed that in addition to its installation in accordance with standards, the control is properly timed and phased, the geometric design of the intersection is adequate and the adjacent traffic signals are properly coordinated. Warrants are necessary but not sufficient to indicate the need for signal control at an intersection. As described earlier in Section 6.3 of Chapter 6, the safety professional must still use judgment before opting for traffic signal installation. If one or more of the warrants is satisfied by a location, the following questions may be considered:

1. Does observation of the intersection reveal any problem that requires a solution? There may not be a real problem. Refer to Chapter 3 for proper methods for evaluating a potential problem intersection.
2. Is the problem worthy of a solution? Often there are so few motorists experiencing the problem that it is simply not realistic to solve it (often the application of the warrant guidelines will screen out such locations, but not always). It may be that certain movements should be prohibited instead.
3. Is the delay for cross-street traffic acceptable, considering the effect a traffic signal will have on the main street traffic? Determine the function of the intersection as it relates to the overall street system. A system of major streets should be designated to channel major flow from one section of the region to another. The major street system should be considered when the intersection control is selected.
4. Would delay to minor street motorists and pedestrians be reduced? Often, such delay will remain unchanged or even increase when a signal is installed.
5. Are cross-street motorists or pedestrians making unsafe maneuvers to enter or cross the main street?
6. If there are apparent problems that a traffic signal could solve, are there less restrictive measures that could be applied to alleviate the problems? If so, they could be tried before installing a traffic signal. Alternatives may include:
    - Install warning signs in advance of the intersection;
    - Increase the size of existing warning and/or STOP signs;
    - Reposition warning and/or STOP signs for better visibility;
    - Improve sight distance by removing obstructions or relocating STOP lines;
    - Install speed-reducing measures;
    - Install a flashing beacon on stop-controlled approaches;
    - Install flashing beacons on advance warning signs;
    - Add one or more lanes on minor street approaches;
    - Improve intersection geometrics;
    - Improve roadway lighting;
    - Restrict one or more turning movements if acceptable alternative routes are available;
    - Install all-way stop control;
    - Construct a roundabout; and
    - Increase enforcement of existing traffic control measures.

7.1.4 Traffic Signal Control Modes of Operation

There are no clear-cut demonstrated relationships between the mode of signal control and crash experience. However, it is recognized that there is a relationship between pre-timed, semi-actuated, full-actuated, or density control and the occurrence of stops at the intersection. Intuitively it is expected that actuated control should be capable of providing a safety benefit by reducing unnecessary stops. Similarly, coordinated signal system operation should provide similar benefits by minimizing stops.

The most significant identifiable contributing factors to the frequency of crashes at a signalized intersection is the signal display itself (number, location and size of signal indications) and intersection geometry. These characteristics appear to have a much larger influence on crashes than the mode of signal control utilized.

7.1.4.1 Pre-Timed Control

Pre-timed control operates within a fixed cycle length using preset intervals. This mode of operation is best suited where traffic patterns and volumes are predictable and do not vary significantly from day-to-day. Signal controller units operated in the pre-timed mode usually can accommodate several cycle lengths, splits and offsets. Potential advantages include the following:

- The consistent starting time and interval duration of pre-timed control facilitate coordination with adjacent traffic signals. It also provides more precise coordination than traffic-actuated control, especially when coordination is needed with adjacent traffic signals on two or more intersecting streets in a grid system, or between very closely spaced intersections.
- Pre-timed control is not dependent on the detection of approaching vehicles for proper operation. Therefore, the operation is not adversely affected by such conditions as a stopped vehicle or construction work within the detection area.
- Pre-timed control may be more acceptable than traffic-actuated control in areas where large and fairly consistent pedestrian volumes are present.
- The total cost of a pre-timed installation is less than a traffic-actuated installation because there is no detection equipment.
- The timing of pre-timed control is not as complex as actuated control. There are fewer decisions required and time settings tend to have a more straight-forward effect on traffic operations than with actuated control.

7.1.4.2 Actuated Control

Actuated control differs from pre-timed control in that green intervals are not of fixed length, but are determined (within certain limits) by the changing traffic flow at the intersection. The length of cycle and the sequence of intervals may or may not remain the same from cycle to cycle. In some cases, certain intervals may be omitted when there is no actuation or demand from waiting vehicles or pedestrians. Full-actuated operation is generally used where the intersection operates independently (for example, not part of a signal system) and where traffic demands are highly variable. Potential advantages include the following:

- Traffic-actuated control may provide maximum efficiency at intersections where fluctuations in traffic cannot be anticipated and programmed with pre-timed control.
- Traffic-actuated control may provide maximum efficiency at complex intersections where one or more movements are sporadic or subject to variation in volume and where multiple phasing is required to accommodate left turns.
- Traffic-actuated control may provide maximum efficiency at intersections unfavorably located within progressive pre-timed systems, where interruptions of major street traffic are

undesirable and must be held to a minimum in frequency and duration. A background time cycle may be superimposed upon the operation to effect coordination with nearby signals.

- Traffic-actuated control may minimize delay during periods of light traffic because no green time is provided to phases where no traffic demand exists.
- Traffic-actuated control permits continuous control during all hours, whereas pre-timed signals may be switched to flashing operation during low-volume hours to avoid unnecessary delays.
- Traffic-actuated control tends to reduce crashes associated with the end of a green interval when drivers must make a decision about whether to stop in response to the yellow light.

7.1.4.3 Semi-Actuated Control

Semi-actuated control requires detection for the minor movement(s) and is especially effective in coordinated signal system operation along a major street. In coordinated signal system operation, a background cycle is imposed on the operation of the signals at each of the intersections in order to maintain progression.

At isolated intersections (not part of a signal system), semi-actuated control interrupts the major street traffic flow only when required for minor street vehicular or pedestrian traffic. Such interruptions are restricted to the minimum time required.

At intersections where the minor street volume is less than 20 percent of the major street volume, there is little difference between semi-actuated and full-actuated control in terms of delay and vehicle stops. At higher proportions of minor street volumes, full-actuated control performs significantly better than semi-actuated control.

7.1.4.4 Signal System

A traffic signal system consists of two or more signalized intersections operated in coordination. The objective of signal system operation is to improve the flow of traffic along a major street or throughout a network of streets. Signal systems may be relatively small, or fairly large and complex.

Coordination of signals within a system is one of the most cost-effective methods of reducing stops, reducing delays, decreasing crashes, reducing average travel times and decreasing air pollutant emissions. The positive benefits of signal coordination can be demonstrated by the results of a study of 11 signalized intersections over a 1.9-mile length of arterial street in Naperville, IL.[25] Reductions of 15 to 18 percent in peak hour travel times through the system were observed. During the same peak hour periods, crash frequency was reduced 12 percent after implementation of the system operation.

7.2 Traffic Signal Phasing

7.2.1 Basic Principles

A traffic signal phase is the combined right-of-way, yellow change and red clearance intervals in a cycle that are assigned to an independent traffic movement or combination of movements.[1] The "phase sequence" is the predetermined order in which the phases of a cycle occur.

The phasing and sequencing of a traffic control signal have the potential to affect both the safety and efficiency of vehicle and pedestrian traffic movement at the intersection. The goals of maximizing safety and minimizing delay and stops often compete with one another. Care must be taken to achieve an appropriate balance at any intersection.

The analysis of traffic data, geometric design and signal phasing for an intersection must be a coordinated effort. The objective should be to devise the simplest design and the minimum number of phases that will accommodate existing and anticipated traffic demand (motor vehicle, pedestrian and bicycle) safely and efficiently, without disenfranchising any users.

7.2.2 Left-Turn Phasing

One of the more important phasing issues is the treatment of left turns. Left turns may be accommodated as one of four possible modes:

- *Permissive-only mode:* turns are made on the circular green signal indication after yielding to oncoming traffic and pedestrians.
- *Protected-only mode*: turns are made only when the left turn green arrow signal indication is displayed.
- *Protected and permissive mode*: both modes occur on an approach during the same cycle.
- *Variable left-turn mode:* the operating mode changes among the protected-only and/or the protected/permissive mode and/or the permissive-only mode during different periods of the day.

Crashes involving left-turning vehicles colliding with opposing vehicles and/or pedestrians are a major concern at some signalized intersections. In addition, as left-turning volumes and opposing through traffic volumes increase, a point is reached where it is difficult for left-turning traffic to find adequate gaps when operating in the permissive-only mode. While phases for protecting left-turning vehicles are the most popular and most often added phases, these separate phases reduce the available green time for through traffic and tend to increase total intersection delay. As a result, other methods of handling left-turn conflicts should also be considered. Potential solutions include the prohibition of left turns and geometric improvements. Both are outlined below.

7.2.2.1 Left-Turn Prohibition Option

Left turns can be prohibited on a full- or part-time basis. The following should be taken into account when considering a left-turn prohibition:

- Volume and classification (type) of vehicles diverted;
- Adequacy of alternative routes that are likely to be utilized (environmental considerations, pavement and bridge structural capacity, safety features, adjacent land use, etc.);
- Effect on transit service;
- Additional travel time and distance; and
- Enforcement needs (particularly during initial week or two of change).

The overriding issue is whether the left-turn prohibition will solve the problem or simply move the problem elsewhere.

7.2.2.2 Geometric Improvement Option

The provision of a separate left-turn lane will alleviate the left-turning problem somewhat by providing storage space in which turning vehicles can wait for an acceptable gap in opposing traffic.

Another option is to reconstruct the intersection. Chapter 5 presents alternative concepts that could be considered.

7.2.2.3 Analysis

Whether or not protected left-turn phasing should be provided is a decision that must be based on an engineering analysis. The following factors should be considered:

1. *Crash Experience*—Consider left-turn phasing if a critical number of left-turn crashes has occurred. The analyst should pre-determine the critical number(s) of crashes based on an analysis of comparable intersections throughout the jurisdiction, county, or state.

2. *Delay*—Excessive delay to left-turning vehicles is a major reason for installing protected left-turn phases. However, it must be recognized that additional signal phases frequently lead to increased total intersection delay. Left-turn phasing should be used selectively where excessive delays are encountered by left-turning vehicles.

Consider the installation of a protected left-turn phase if left-turn delay exceeds a predefined threshold (either intersection-wide or at the individual vehicle level). Existing signal timing should first be evaluated to determine if a more efficient operation can reduce delay.

3. *Capacity*—At a new intersection where delay and crash data are not yet available, consider protected left-turn phasing when the product of the volume of left-turning traffic and volume of opposing traffic (V_L x V_O) during the typical peak hour exceeds the threshold values in Table 7–2.

Table 7–2: Product Warrant for Protected Left-Turn Phases

Number of Opposing Lanes	Threshold Value (V_L x V_O)
1	50,000
2	90,000
3	110,000

Source: Adapted from 9

Typically, an average of two vehicles can turn left during each phase change interval. This may be considered the minimum capacity for left turns as a permissive movement, even if opposing through traffic is so heavy that no left turns can be made during the green interval. This capacity will therefore depend on cycle length because shorter cycles will result in more phase changes per hour. A cycle length of 60 sec., for example, results in a minimum left-turn capacity of about 120 vehicles per hour.

A capacity warrant should not normally be used as the sole criterion for determining the need for protected left-turn phasing at an existing signalized intersection. A left-turn volume that satisfies the capacity criterion merely indicates a need for further study of left-turn delay and crash experience.

4. **Other Factors.** Other factors that may suggest the need for protected left-turn phasing include:

- At some intersections, the vertical and/or horizontal roadway alignment or obstructions in the median may block the visibility available to the left-turning driver. Suggested criteria for left-turn sight distances are presented in the AASHTO Green Book.[10] At intersections where adequate left-turn sight distance is not available, protected left-turn phasing should be used or left-turns should be prohibited.
- High vehicle speeds and/or multiple lane approaches may make it difficult for left-turning drivers to judge gaps in oncoming through traffic. A study in Kentucky[16] found that when protected-only left-turn phasing was replaced with protected/permissive phasing on roads with speed limits above 45 mph, there was a "dramatic increase" in left-turn and total crash frequency. Generally, protected-only left-turn phasing should be strongly considered where speed limits are higher than 40 or 45 mph.
- Unusual geometrics or traffic conditions may complicate the driver's task and necessitate left-turn phasing. Examples include (1) approaches where dual left-turn lanes are provided, although there are instances where these have operated successfully in a permissive mode, and (2) approaches where left-turning traffic conflicts with a high volume of pedestrians during a permissive phase.

The *Highway Design Handbook for Older Drivers and Pedestrians*[8] recommends more extensive use of protected-only left-turn phases to assist older drivers. The complex decision-making process required for permissive left-turns, especially under heavy traffic conditions, has been identified as a special problem for older drivers. Several studies are cited in the report indicating that older drivers are over-represented in left-turn crashes. The report also cites several studies that found a decreasing understanding of protected/permissive phasing with increased age.

7.2.2.4 Potential Safety Benefits

A before-and-after study of 24 intersections in Kentucky[9] found an 85 percent reduction in left-turn crashes after installation of protected left-turn phasing. However, rear-end crashes increased, yielding a net decrease of only 15 percent in total crashes. Injury crashes decreased by about 15 percent. Similarly, a study by the Iowa Department of Transportation[11] found an average crash reduction of 38 percent when protected left-turn phases were added to an existing signal and an average reduction of 58 percent when both a protected left-turn phase and left-turn lane were added.

A study in Winston-Salem, NC[12] evaluated six locations where left-turn crashes were treated by adding a protected left-turn phase. In four cases, the left-turns were fully protected, and in two cases, protected/permissive phasing was used. The overall reduction in left-turn crashes was 39 percent. Overall, left-turn crashes declined in five of the six cases. At one intersection, left-turn crashes increased after the phase was installed. This was judged to have occurred because of the peculiar geometry of the intersection. If this case were not included, the average reduction in left-turn crashes would approach 75 percent.

A study of 17 intersections in Florida[15] indicated that when protected-only phasing was replaced with protected/permissive operation, left-turn crash frequency per year increased from an average of 0.5 (per intersection) to an average of 2.5. In addition, total intersection crash frequency per year increased from an average of 12.0 to 14.5. However, when protected/permissive operation was changed to protected-only at 11 intersections, annual left-turn crashes reduced from 5.0 (per intersection) to 0.5, but total intersection crashes increased from 19 to 31.5.

The City of Indianapolis, IN studied a group of 14 signalized intersections where "unwarranted" protected left-turn phases were removed.[14] After removal, the average frequency of left-turn crashes increased 24 percent, but right-angle crashes declined 22 percent and rear-end crashes declined 23 percent. Total crashes declined 5 percent. The effect on crashes varied considerably from one intersection to another and was directly correlated with traffic volumes and presence of left-turn lanes. It was concluded that removal of protected left-turn phases at low-volume intersections without left-turn lanes will not likely bring an increase in crashes. Removal of protected left-turn phases at high-volume intersections without left-turn lanes will likely result in an increase in left-turn crashes.

7.2.2.5 Implementation

When the decision is made to implement protected left-turn phasing, the following considerations apply:

1. Protect only the approaches that need protection. Protected left-turn phases should only be used where they are warranted and necessary.
2. Protected left-turn phases should generally be traffic actuated. Even at intersections operated in the pre-timed mode, it is possible to actuate the minor movements. Actuation avoids the unnecessary taking of effective green time from the through traffic when left-turn traffic is light.
3. In general, when protected left-turn phases are provided at an intersection, protected/permissive or permissive/protected phasing provides greater efficiency than protected-only phasing. With this type of phasing, the left-turning traffic is given a protected phase during a portion of the cycle, but it also allowed to move during the through traffic phase. This has two efficiency advantages over protected-only phasing.
   - It increases the intersection capacity and will often allow protected left-turn phases to be skipped.

- It is more acceptable to drivers, reducing both left-turn delay and total intersection delay as well as fuel consumption.

7.2.2.6 Protected/Permissive Sequence Options

Where left-turns are permitted during the through traffic phase, protected left-turn phasing can be accommodated as either a protected/permissive sequence or a permissive/protected sequence. Issues to consider during this selection (for example, the left-turn trap with permissive/protected phasing) are documented in the ITE *Traffic Safety Toolbox*.[5]

A study of signalized intersections in Mesa and Scottsdale, AZ[17] compared crash rates for protected/permissive and permissive/protected phasing. This study considered only collisions between left-turning and opposing vehicles (not rear-end or side-swipe collisions that may be related to left-turn maneuvers). The study found no significant difference in either property damage or injury crash rates between the two alternative phase sequences. It was noted, however, that there is a considerably higher crash rate for protected/permissive operation that uses third-car detection (the protected left-turn phase is not called unless there are at least three left-turning vehicles queued).

Other studies have produced mixed results. One study found that crash frequency is higher for the protected/permissive sequence compared with the permissive/protected sequence.[32] Another study found this to be true only for intersections with three lanes of opposing traffic, while intersections with two lanes of opposing traffic had higher crash frequencies for the permissive/protected sequence.[33]

7.2.3 Phasing to Reduce Pedestrian Conflicts

"Crash data consistently show that collisions with pedestrians occur far more often with turning vehicles than with straight-through traffic. Left-turning vehicles are more often involved in pedestrian accidents than right-turning vehicles, partly because drivers are not able to see pedestrians to the left as well."[4] Conflicts between pedestrians and turning vehicles can be substantially reduced by the use of a phasing scheme that separates these movements. A study of exclusive pedestrian phasing[8] found a 50 percent decrease in crashes involving pedestrians at intersections with moderate to high pedestrian volumes when compared with pedestrian phasing that was concurrent with vehicle traffic movement on a paralleling street.

Exclusive pedestrian phase operation (as shown in Figure 7–2) is often referred to as the "scramble system" because pedestrians are permitted to use all crosswalks and walk diagonally across the intersection during the pedestrian phase. This phasing scheme is primarily used in business areas or other locations where heavy pedestrian crossing volumes conflict with turning vehicle movements. Exclusive pedestrian phases tend to be inefficient where street crossing distances are large or where pedestrian signal compliance is poor. Figure 4–28 in Chapter 4 is a photograph of pedestrians crossing an intersection during an exclusive pedestrian phase.

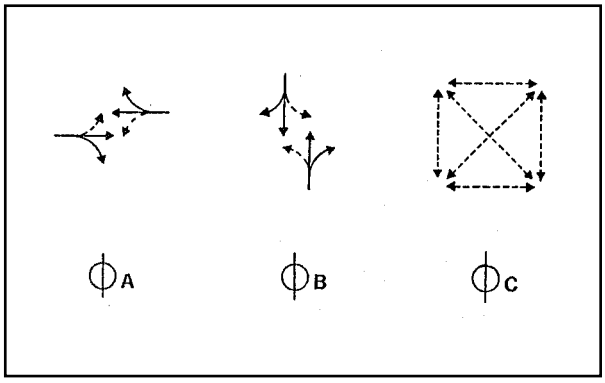

Figure 7–2: Exclusive Pedestrian Phase Sequence
Source: Northwestern University Center for Public Safety

Exclusive pedestrian phases may "make it difficult for pedestrians who are blind or visually impaired to recognize the onset of the walk interval, particularly at locations where right-turn-on-red is permitted. In addition, there is no vehicular flow to aid in crossing straight to the destination corner. Ongoing research is evaluating strategies for accessible pedestrian signal

installations at intersections with exclusive pedestrian phasing."[6]

Share-the-phase operation (Figure 7–3) can be used to an advantage on wide streets where an exclusive pedestrian phase would be inefficient. Separate left- and/or right-turn lanes should be provided to store turning vehicles during pedestrian crossing intervals. Desirably, changeable message signs should be used to indicate NO LEFT TURN and NO RIGHT TURN during the pedestrian crossing phase.

Section 4.1.4.2 of Chapter 4 provides additional guidance on signal phasing issues for pedestrians.

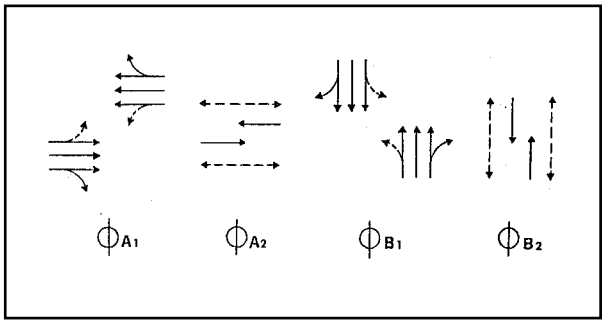

Figure 7–3: Share-the-Phase Sequence
Source: Northwestern University Center for Public Safety

7.2.4 Signal Preemption and Priority Control

Another area of growing interest is the use of emergency vehicle preemption and priority control for transit vehicles. Emergency vehicle preemption is used to assist emergency vehicles in reaching their destination quickly. The emergency vehicle transmits a signal that is received by the intersection controller, which in turn then safely terminates the signal phase that it is in and starts the signal phase requested by the approaching emergency vehicle. As a result, traffic is cleared from in front of the emergency vehicle, enabling it to proceed through the intersection green light at speed, rather than having to work its way through queued traffic, then slow to a stop at the intersection and cross against signal indications. In areas where preemption is used, it has proven to greatly increase the safety of the emergency vehicles and substantially reduce response times.

Similarly, priority control for transit vehicles is gaining considerable momentum across the nation. For transit priority, the transit vehicle transmits a signal to the controller. Rather than abruptly terminating the current signal phase, the controller either gives the transit vehicle approach an extended green or an early green. An extended green is given when the transit vehicle is approaching the intersection towards the end of the green phase that services the movement that the bus is operating in. In most locations, the green phase is extended up to 10 sec. in an attempt to allow the bus to get through the intersection without having to wait through one cycle. An early green is given when the bus is detected after the end of green for the phase that services the bus. After receiving the priority call from the bus, the controller shortens the other signal phases by a few seconds to bring the bus approach green phase 5–10 sec. earlier than it normally would.

Signal preemption is commonly used at railroad-highway grade crossings with active control that are located near a signalized intersection. The normal sequence of intersection operations should be preempted upon the approach of trains. The preemption sequence first permits stored traffic to clear the tracks. After track clearance, signals may be placed on flashing operation or solid green indications to permit movements that do not cross the tracks. Additional detail on signal preemption at rail-highway grade crossings is provided in Section 6.5.2 of Chapter 6.

7.2.5 Flashing Operation

There are two primary reasons for flashing a traffic signal: (1) reduce the level of control when traffic volume is low and (2) provide a safe method of control when a signal is inoperative. Occasionally, a signal may also be flashed as part of a preemption sequence, as noted above.

While a traffic signal may be needed at an intersection during much of the day, it is often the case that the signal is not needed all the time. During such times, total delay at the intersection may be reduced if the signal is operated in the flashing mode. Even an actuated signal may operate more efficiently when placed in flashing mode during periods of low traffic volumes, as illustrated in Figure 7–4. Pedestrian signals should be dark during flashing operation.

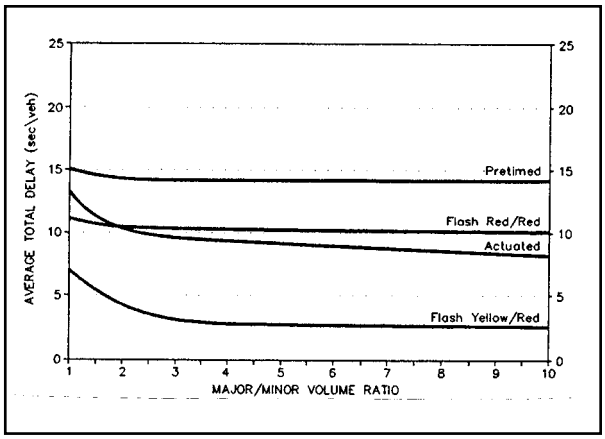

Figure 7–4: Comparison of Average Vehicle Delay for Modes of Signal Operation
Source: 24

In general, when a signal is operated in the flashing mode during low-volume periods, it is more efficient if the major street is flashed yellow and all other streets are flashed red. However, it must be recognized that red/yellow flashing operation also comes with a risk of increased numbers of right-angle crashes. One study concluded that "drivers facing a flashing red indication do not appear to understand that the conflicting traffic may be facing a flashing yellow."[24] Another study of 19 signalized intersections in Winston-Salem, NC[12] concluded that when red/yellow flashing operation was discontinued, right-angle crashes (during hours when flashing operation had been in place) were reduced at every intersection with an average reduction of 77 percent.

A study of more than 200 signalized intersections in Texas found that flashing operation in urban areas resulted in statistically significant increases in right-angle crashes and in crash severity.[24] Interestingly, about 56 percent of the intersections did not have any crashes during the 4-year study period and there were no right-angle crashes at any of the rural intersections with flashing operation. The study found a correlation between the absence of right-angle crashes at the intersections under normal signal operation and the lack of such crashes under flashing operation. The study concluded that intersections that had experienced zero or one crash in the most recent 2-year period while the signal was in normal operation were good candidates for consideration of flashing operation at nighttime.

A set of suggested guidelines for the use of flashing operation is provided below.[24]

- For low-volume periods, flashing operation should not be used if the signal is capable of operating in the actuated mode.
- For low-volume periods, flashing operation for a pre-timed signal may be considered if, for at least 4 hours:
  1. Major street two-way traffic volumes are less than 500 vehicles per hour, and
  2. Minor street higher approach volume is less than 100 vehicles per hour, and
  3. There has been no more than one right-angle crash at the intersection in the preceding 2 years of normal signal operation.
- For low-volume periods that meet the preceding criteria, red/red flash should be used if there are six or more lanes on the major street or if the major-to-minor street volume ratio is less than three.
- When flashing operation is initiated due to signal malfunction, it generally should be operated in red/red flash.

7.3 Principles of Traffic Signal Timing

7.3.1 General Considerations

The objectives of traffic signal timing include:

- Provide for the orderly and equitable accommodation of vehicle and pedestrian traffic;
- Minimize delay to vehicle and pedestrian traffic;
- Minimize the number of vehicles that must stop at the intersection;
- Reduce the potential for crash-producing conflicts;
- Maximize the capacity of each intersection approach; and
- Provide frequent gaps in the dominant traffic flow to accommodate pedestrian crossings.

These objectives are not always compatible. For example, to reduce the potential for crashes, multiple phases and consequently longer cycle lengths may be required. Similarly, complex traffic operations, high-speed turning vehicles and long cycle lengths may act as substantial disincentives for pedestrian travel. Accordingly, it is necessary to exercise professional judgment to achieve an appropriate balance among these objectives to reasonably accommodate all intersection users.

7.3.2 Cycle Length

Short cycle lengths generally yield the best performance in terms of reducing the average delay per vehicle, provided that the capacity of the cycle to pass vehicles is not exceeded. Longer cycle lengths have a higher theoretical capacity because the start-up lost times are a smaller proportion of the overall cycle length. However, the increase in capacity obtained by increasing cycle lengths becomes marginal for cycle lengths in excess of 60 sec. for two-phase operation and for cycle lengths in excess of 80 sec. for multi-phase operation. In addition, as a practical matter, traffic flows usually cannot sustain saturation flow conditions for excessively long green intervals, negating the theoretical capacity advantage of longer cycle lengths. A cycle length of 120 sec. is usually considered the maximum desirable cycle length to be used, regardless of the number of phases.

Excessively long cycle lengths tend to reduce both intersection efficiency and safety because long cycles result in longer vehicle and pedestrian wait times. "When this occurs, impatient drivers and pedestrians often commit traffic control violations."[4] Long periods of unused green time on some or all approaches, or excessive delays to waiting vehicles while a thinned-out flow of traffic with large gaps continues to hold the green, indicate inefficient signal operation. If the cycle lengths are excessive or if inefficient use of the green time is observed, then traffic performance at the intersection can probably be improved. This improvement may require revised design, timing changes, or control equipment update.

7.3.3 Phase Change Intervals—Motor Vehicles

Many agencies use a combination of yellow change and red clearance intervals to comprise the phase change interval. This practice is intended to ensure that a driver traveling at the appropriate speed will be able to either (1) comfortably stop before reaching the intersection or (2) clear the intersection before conflicting traffic receives a green indication (if close to the intersection at the onset of the yellow change interval). A method for determining appropriate phase change intervals has been documented by ITE.[*20]

* The calculation requires values for perception/reaction time of the driver, deceleration rate for stopping vehicle, vehicle speed, approach grade (uphill, downhill), intersection width and design vehicle length. The standard value used for the perception and reaction time of drivers approaching a signalized intersection is 1.0 sec. The *Highway Design Handbook for Older Drivers and Pedestrians*[8] concludes that the 1.0-sec. reaction time is appropriate for both older and younger drivers, but that the use of a 1.5-sec. reaction time "is well justified when engineering judgment determines a special need to take older drivers' diminished capabilities into account."

The timing of phase change intervals can affect signalized intersection crash rates. A study examined the relationship between phase change interval timing and crash rates at 91 intersections in eight metropolitan areas throughout the United States.[21] The intersections were sorted into eight relatively homogeneous clusters based on cross street width and crossing time, implied deceleration rates required by phase change interval timing and average daily traffic. Crash rates were adjusted to account for the frequency of signal changes relative to average cycle length. The study found that intersection cluster groups with "less adequate" phase change intervals had higher crash rates than those with "more adequate" phase change intervals.*

A study of the effect of phase change interval length on driver response at 20 signalized intersections in New York[22] found that yellow change intervals that were shorter than calculated using the ITE procedure were associated with higher frequencies of red-light running. However, excessively long yellow change intervals can be a problem as well. A recent study confirmed that drivers do adapt to an increase in the length of the yellow change interval resulting in "a slightly lower probability of stopping for a given travel time to the intersection at the yellow onset."[30] The MUTCD indicates that the yellow change interval should be set within the range of 3 to 6 sec. and many signal controller units will not permit settings outside of this range. If the phase change interval needs to be near the top of this range or beyond, the additional time is sometimes provided as part of a red clearance interval.

A study of the effect of red clearance interval length in Detroit, MI found that sites where the red clearance interval was timed using the ITE procedure had red-light running angle crash rates that were 72 percent less than those for intersections with deficient red clearance intervals.[31]

The Swedish National Road Administration has taken a different approach for dealing with red-light running. It has developed a sophisticated strategy for timing isolated, high-speed signalized intersections referred to as "LHOVA."[7] One element of this strategy, which is designed to reduce red-light-running and the resultant right-angle collisions, utilizes a variable red clearance interval (although the use of variable phase change intervals is not currently permitted by the MUTCD).

The change interval required for left-turn phases depends on the path followed by the left-turning vehicle, speed of turn and the direction of movement of traffic conflicts on the subsequent phase. Many agencies use a standard change interval for all left-turn phases of between 3 and 4 sec. of yellow change and between 0 and 1 sec. of red clearance. The ITE procedure[20] can also be used to calculate the change interval for a left-turn phase.

7.3.4 Phase Change Intervals—Bicycles

Bicyclists typically cross intersections under the same signal phases as other traffic. The greatest risk to bicyclists is during the phase change intervals.[2]

The change interval calculated for motor vehicles will generally be adequate for bicyclists at most standard intersections. However, at wide intersections change intervals based on bicyclist characteristics may be somewhat longer than those based on motor vehicles. In these cases, a red clearance interval as long as local policy will permit is the preferred approach (rather than an extended yellow change interval). These intersections should be reviewed on a case-by-case basis to determine whether a longer red clearance interval can be implemented without other problems occurring (for example, such as motorists taking advantage of the red clearance interval or increases in collisions due to progression or capacity reductions).[2]

* The phase change intervals ranged from 10 percent shorter than recommended by the ITE procedure to 10 percent longer. The crash rate for the group with the least adequate phase change intervals was significantly higher than the group with the most adequate phase change intervals. Also, the number of drivers who did not clear the intersection during the phase change interval sharply increased for the groups with the least adequate phase change intervals.

7.3.5 Green Intervals

Although "snappy" operation with relatively short green intervals is usually considered desirable for efficient operation, caution must be exercised in timing green intervals that are too short. When approaching a signalized intersection, drivers who see their signal change to green have an expectation that the signal will remain green for some reasonable amount of time. To meet driver expectations, major movement green intervals generally should not be less than 12 to 15 sec. long for pre-timed operation and not less than 8 to 10 sec. long for actuated operation. Because the actual length of green indications provided are usually extended beyond the minimum green setting, a smaller time setting than the minimum for pre-timed operation is considered acceptable.

7.3.6 Pedestrian Intervals

In order to accommodate pedestrian crossings, the minimum length of a concurrent vehicle green interval can be calculated as:

$$G_{min} = P + \frac{D}{S} - Y$$

Where

G_{min} = minimum vehicle green interval (sec.)
P = pedestrian start-off time (sec.)
D = walking distance (ft.)
S = walking speed (ft.)
Y = yellow change interval (sec.)

The purpose of the start-off time *(P)* is to permit all pedestrians standing at the intersection to begin crossing the street. The pedestrian start-off time should normally be at least 7 sec. This start-off time is usually adequate for signalized intersections where pedestrian volumes average less than about 20 pedestrians per cycle (total crossing in all directions). Where pedestrian volumes are higher (such as a downtown, commercial, or tourist area), longer start-off times and walk times may be desirable. The *Highway Capacity Manual* provides a formula for estimating this entire walk time as a function of pedestrian volume and effective crosswalk width.

D/S is the amount of time required for the pedestrian to actually cross the street after stepping off the curb. The crossing distance, *D*, should be the full distance to the far side of the traveled way or to a median with raised curbs and of sufficient width to store waiting pedestrians. The crossing distance is measured along the centerline of the crosswalk or normal pedestrian crossing path (if no crosswalk is designated).

Y is the length of the yellow change interval for concurrent vehicle traffic. The MUTCD permits the entire change period (yellow change plus red clearance) to be used. However, it is generally desirable, if feasible, to use only the yellow change so that pedestrians complete their crossings before the beginning of the red clearance interval.

Where pedestrian signal indications are provided (WALKING PERSON and UPRAISED HAND symbols), the following principles should be considered. Additional guidance on pedestrian signal phasing and timing is provided in Section 4.1.4 in Chapter 4.

- The walk interval should be at least equal to the pedestrian start-off time. Provisions in the MUTCD indicate that the pedestrian walk interval should be at least 7 sec. long. However, under unusual circumstances, it is acceptable to reduce the start-off time (and walk interval) to as little as 4 sec.
- Some agencies provide a walk interval that is long enough to allow pedestrians to at least reach the middle of the street, to encourage them to finish crossing during the pedestrian clearance interval.

- When a pre-timed green interval for vehicle traffic is longer than the minimum amount needed for pedestrians (G_{min}), the extra time should be added to the walk interval. The flashing upraised hand interval should not be made longer than $D/S - Y$. An excessively long pedestrian clearance could result in a loss of credibility among pedestrians.
- The pedestrian clearance interval (flashing UPRAISED HAND) is normally equal to $D/S - Y$. Current signal controller units typically terminate the flashing UPRAISED HAND indication at the end of the concurrent vehicle green interval, and display a steady UPRAISED HAND indication during the vehicle yellow change interval. This is intended to encourage pedestrians still in the crosswalk to complete their crossing without delay. However, even though the pedestrian signal may show a steady UPRAISED HAND during the vehicle yellow change interval, this time is still considered to be part of the time available for pedestrians to finish crossing the street.
- It is recognized that some agencies continue the flashing UPRAISED HAND indication during the vehicle yellow change interval. In this case, the flashing UPRAISED HAND should be displayed for the full amount of D/S.

If there is a possibility that pedestrians will use an intersection where the signal is operated in the actuated mode, pedestrian detection and signal indications should be provided. The controller unit should only display the walk and pedestrian clearance intervals when a pedestrian is detected. These intervals are timed concurrently with the appropriate vehicle green interval, with the walk interval typically beginning at the same time as the vehicle green interval.

An emerging aspect of traffic signal timing that is receiving considerable attention is the use of accessible pedestrian features to accommodate pedestrians with visual disabilities. These accessible pedestrian indications provide information to the pedestrian through audible tones, verbal messages, or vibratory feedback. Future versions of the MUTCD may require increased use of accessible pedestrian features. A comprehensive overview of these features is presented in Section 4.1.4.6 of Chapter 4.

7.4 Designs that Address Selected Safety Issues

7.4.1 Dilemma Zone Protection

The manner in which the green is terminated becomes a special concern on high-speed approaches (where approach speeds are greater than 40 mph). Over a certain range of distances from the intersection, depending on the speed, drivers may react unpredictably to the onset of a yellow light. This range of distances, within which drivers are often indecisive, is known as the "dilemma zone."

The upper limit of the dilemma zone tends to occur approximately 5 sec. travel time from the intersection. The lower limit is about 2 to 3 sec. from the intersection. On high-speed approaches, it is desirable to avoid terminating the green while a vehicle is within this dilemma zone range.

Actuated control permits a wide range of detection locations while still maintaining efficient intersection operations. On high-speed approaches where dilemma zone protection may be desired, the detection should be located in advance of the beginning of the dilemma zone for the anticipated speed of traffic on the approach. Generally, a location that is 5 sec. travel distance in advance of the intersection is appropriate.

Although a 5-sec. detection setback provides dilemma zone protection for vehicles traveling at the design speed, it may terminate the green for a lower speed vehicle while that vehicle is still in its dilemma zone. An alternative design protects the lower speed vehicle with a strategically placed second detection area, as illustrated in Figure 7–5.

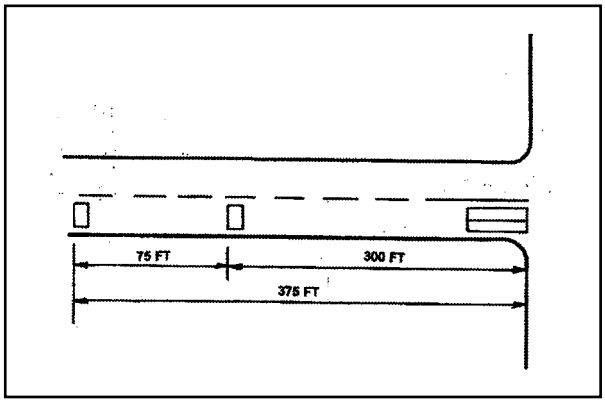

Figure 7–5: Multiple Detection Areas for Dilemma Zone Protection
Source: Northwestern University Center for Public Safety

The first detection area is located as before, 5 sec. travel time upstream of the intersection (for example, 375 ft. for 50 mph speed traffic, as shown in Figure 7–5). A second detection area is located upstream of the dilemma zone for traffic traveling 10 mph less than the design speed (300 ft. from the intersection, upstream of the 40 mph dilemma zone). An extended-call setting of 1.0 sec. holds the first detection long enough to allow a vehicle going 50 mph to reach the second detection area without gapping-out.

However, a slower vehicle will not reach the second detection area before this extension expires and will gap-out before reaching its dilemma zone. The extended-call setting on the second detection is made long enough so the combination of the two extensions equals the desired minimum gap.*

7.4.2 Active Warning Signs for High-Speed Approaches

The Province of British Columbia, Canada developed the following set of warrants for installation of active advance warning signs:[28]

- View of the traffic signals is obstructed because of vertical or horizontal alignment;
- There is a grade in the approach to the intersection that requires more than the normal braking effort;
- Posted speed limit on the roadway is at least 70 km/h (45 mph); or
- Motorists are exposed to many kilometers (miles) of high-speed driving (regardless of posted speed limit) and encounter the first traffic signal in a developed community.

For each of these situations, the use of an active, advance warning sign such as PREPARE TO STOP WHEN FLASHING may be useful to prepare drivers for the upcoming signal (Figure 7–6). The flashing lights on such signs are typically activated near the end of the green interval and remain active until the end of the red indication.

Figure 7–6: Active Advance Warning Sign

* There are two controller unit options that significantly affect the ability to provide desired dilemma zone protection.

- "Last car passage" option should not be used if dilemma zone protection is desired. Last car passage is a feature that ensures that the last vehicle detected prior to a gap-out will receive its full passage time before the green can be terminated for that phase. This option should generally not be used, because it may result in a "trailing vehicle" being caught in its dilemma zone when the green ends for the last detected vehicle.
- "Simultaneous gap-out" ensures that, when two phases are timing concurrently, both must simultaneously reach a point of being committed to terminate (gap-out or max-out) before the greens can end. If only one of the phases has gapped-out, that phase continues to time passage intervals based on vehicle calls until its companion phase terminates. This ensures that both phases are free of vehicles in the dilemma zone when the green is terminated.

With actuated control, the end of the vehicle green interval is variable from cycle to cycle. If vehicle detection is located 5 sec. in advance of the intersection for dilemma zone protection, then the closest approaching vehicle of concern will be at least 5 sec. from the intersection when a gap-out occurs. Placement of the active warning sign in the vicinity of the 5-sec. detection location and activating it when gap-out occurs will provide the proper message to approaching drivers. If the phase has been extended until it approaches the maximum green setting, the warning sign should be activated 5 sec. before the max-out can occur.

Where it is desired to locate the active warning sign farther than 5 sec. travel distance from the intersection, some agencies use a "trailing overlap" to extend the green indication for several seconds after the termination of the phase on a gap-out and after the activation of the warning lights. This method activates the warning before the end of the green indication, but has the disadvantage of eliminating the dilemma zone protection provided by the dilemma zone detection.

To overcome this problem, a more advanced active warning system has been developed and tested by the Texas Transportation Institute.[28] The system uses advance detection placed upstream of the dilemma zone detection, as illustrated in Figure 7–7. This advance detection provides the first information about vehicle arrivals on the high-speed approach. By measuring the speed of arriving vehicles at the advance detection, the system can predict when gap-out or max-out will occur before it actually does. The flashers on the active warning sign are activated while the signal is still green, but the green ends prior to the entry of any vehicle into the dilemma zone. This maintains the integrity of dilemma zone protection. The effectiveness of this system in reducing crashes has not been reported to date. However, is has been reported that incidents of red-light running have been reduced 43 percent since the system was installed.

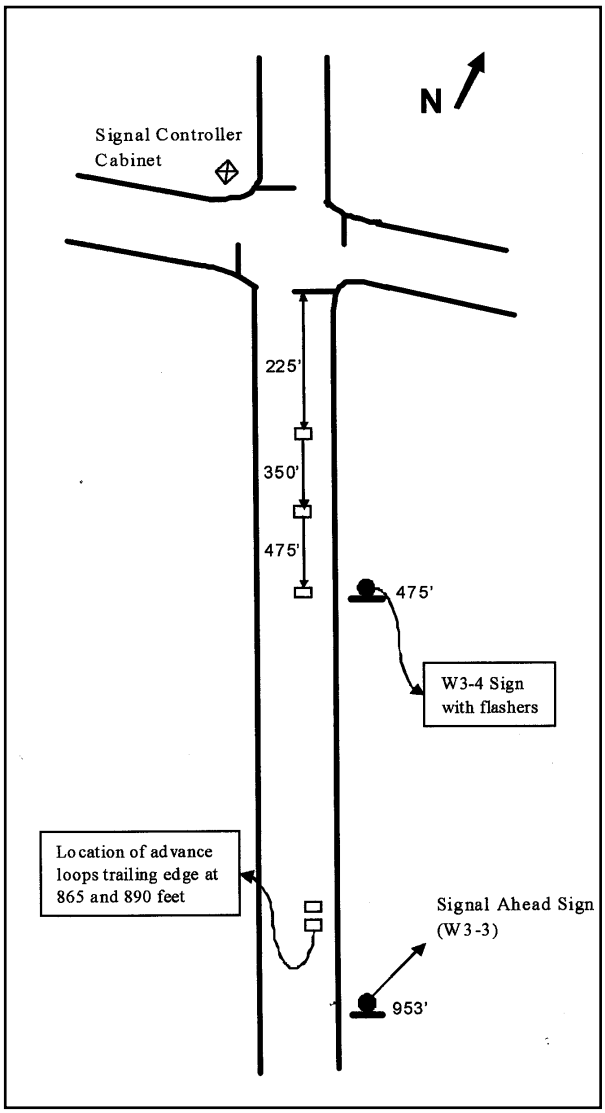

Figure 7–7: Advance Warning Sign System for High-Speed Signalized Intersections
Source: 28

A study of the effectiveness of active advance warning signs for signalized intersections[23] found that such signs resulted in higher speeds for vehicles that approached the intersection on tangent alignments when the signal was green (and hence the sign was not active). On curved alignments, where the signal indications may not be as visible to approaching drivers, mean speeds were slightly reduced during times that the flashing lights were activated. The study also indicated that the SIGNAL AHEAD symbolic sign with flashing lights was more effective and better understood by drivers than the legend PREPARE TO STOP WHEN FLASHING.

7.4.3 Design to Reduce Red-Light Running

Red-light running is defined as "entering and proceeding through a signalized intersection after the signal has turned red."[26] Several engineering countermeasures are available to potentially address the causes of red-light running problems.

- Additional signal heads, larger signal lenses, improved location of signal heads directly in line with approaching traffic and backplates behind signal heads located over the street are all methods of improving visibility. More discussion of signal visibility is presented in Section 7.5.
- Redundancy by providing two red signal lenses within each signal head and the use of LED signals are ways to improve conspicuity suggested by the report *Making Intersections Safer: A Toolbox of Engineering Countermeasures to Reduce Red-Light Running*.[26] More discussion of signal conspicuity is presented in Section 7.5.
- Countermeasures that improve the drivers' ability to stop in response to the traffic signal include improvements to pavement friction, signal-ahead warning signs, advance warning flashers and rumble strips.
- The need to stop can be reduced by proper timing of the traffic signal and use of detection to provide dilemma zone protection. The need to stop can be completely eliminated by removing unwarranted traffic signals, operating signals in flashing mode during low-volume periods, or redesigning the intersection to obviate the need for a traffic signal (for example, a roundabout or interchange).
- Another possible countermeasure is the lengthening of the yellow change or red clearance intervals. A recent study concluded that increases in the length of the yellow change interval "are likely to be effective at reducing red-light violations; however, they are likely to have a more modest effect on red-light related crashes (only crashes that are left-turn related are likely to be reduced)."[30]

In addition to engineering techniques (design and operation of the traffic signal and the intersection), enforcement and education countermeasures are likely to have beneficial impacts on the red-light running problem.

7.5 Treatments to Improve Signal Visibility and Conspicuity

A primary consideration when locating signal faces is *visibility*. Motorists approaching a signalized intersection must be given a clear and unmistakable indication of their right-of-way assignment. Critical elements are the lateral and vertical angles of sight toward a signal face, as determined by typical driver eye position, vehicle design and the vertical, longitudinal and lateral position of the signal face. In addition to being visible, it is also important that the signal indications be *conspicuous*. Conspicuity is affected by the size and brightness of the signal indications and by their contrast against a bright or cluttered background.

The following section presents treatments that potentially improve signal visibility and conspicuity. Pedestrian signal displays are discussed in Chapter 4. The MUTCD provides a complete description of basic traffic signal visibility and conspicuity requirements.

7.5.1 Number of Signal Heads

The MUTCD requires a minimum of two signal faces for the major movement on each approach to the intersection. However, when the approach has more than two lanes, a better approach would be to locate one signal head directly in line with the center of each approach lane as illustrated in Figure 7–8. A similar application is illustrated in Figure 6–18 in Chapter 6. The additional signal heads reduce the likelihood that a driver's visibility of the signals might be blocked by large vehicles, and increases the conspicuity of the signals.

In Winston-Salem, NC, an additional signal head was installed on one or more approaches of six different intersections so that there was one head directly over each lane. At five other intersections, an additional signal head was added to improve advance visibility. For all intersections combined, there was a 48 percent reduction in right-angle crashes.[12]

Figure 7–8: Desirable Signal Face Placement Centered Over Each Approach Lane

7.5.2 Post-Mounted Versus Mast-Arm Installations

Signal faces mounted over the roadway on mast arms or span-wire generally influence the overall safety of intersections compared to post-mounted signals on the roadside. A study of five intersections in Kansas City, MO[29] where post-mounted signals were replaced with mast arm mounted signals, found a 63 percent reduction in right-angle crashes and a 19 percent reduction in rear-end crashes. However, left-turn crashes increased 35 percent. A similar comparison in Iowa[11] found a 72 percent reduction in right-angle crashes, but rear-end and left-turn crashes increased 20 percent and 2 percent, respectively.

When the nearest signal face is more than 180 ft. beyond the STOP line, a near-right secondary signal face must be provided. At other locations, this signal is optional, but within a municipality or in a signal system the use of the near-right signal should be applied consistently. Near-right signals may also be considered in high-speed rural locations where it is necessary to define the stopping point at greater distances from the intersection. When used, near-right signals should be located as near as practical to the STOP line.

In the interest of safety, signal supports and controller cabinets should be placed as far as practicable from the edge of the traveled way, as illustrated in Figure 7–9. Care should be taken to avoid locating signal supports and controller cabinets where they may interfere with the visibility of vehicles or pedestrians.

Figure 7–9: Location of Traffic Signal Support Far From Edge of Traveled Way

The AASHTO Green Book[10] provides guidance on numerous placement criteria including:

- Horizontal clearance for post-mounted signal supports from the face of a vertical curb or from the edge of a shoulder;
- Horizontal clearance for mast arm or span-wire poles from the face of a vertical curb or from the edge of a shoulder;
- Height of a concrete base for a signal support above the ground level at any point; and
- Proper locations of breakaway signal supports within medians.

From a practical standpoint, the signal hardware should not obstruct sidewalks, bus stops, driveways, crosswalks and ramps, or building entrances (Figure 7–10).

Figure 7–10: Undesirable Location of Signal Control Cabinet

7.5.3 Vertical and Horizontal Curves

When the location to be signalized involves horizontal or vertical curves on the approaches, design requires special consideration to ensure adequate signal visibility. To resolve the minimum sight distance issue on vertical curves, signal faces may be raised to maximum heights or supplemented by near-side post-mounted or overhead signals. This is illustrated in Figure 7–11.

Similar techniques can also be applied to horizontal curve approaches. In this case, supplemental near-side signal indications may be placed on the left for right-hand curves or on the right for left-hand curves. These supplemental displays may be post-mounted or overhead as needed to provide adequate sight distance. A schematic of this concept is illustrated in Figure 7–12. A photograph of an application is presented in Figure 7–13.

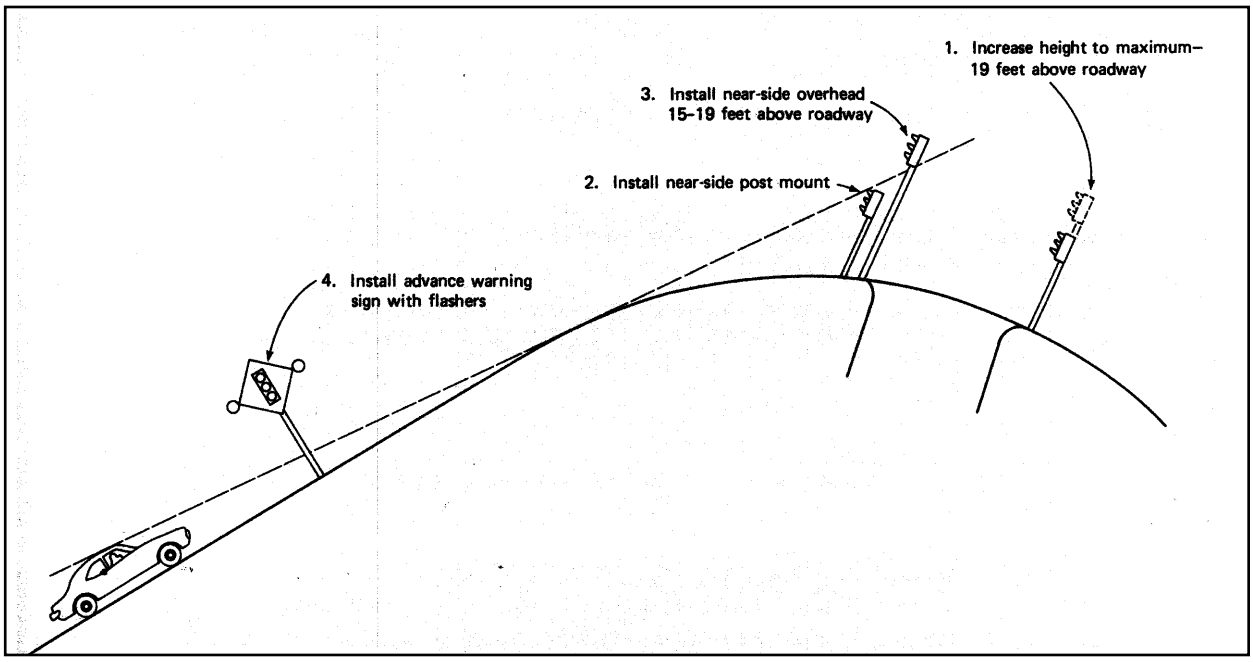

Figure 7–11: Signal Face Adjustments to Provide Adequate Sight Distance at Vertical Curve
Source: 3

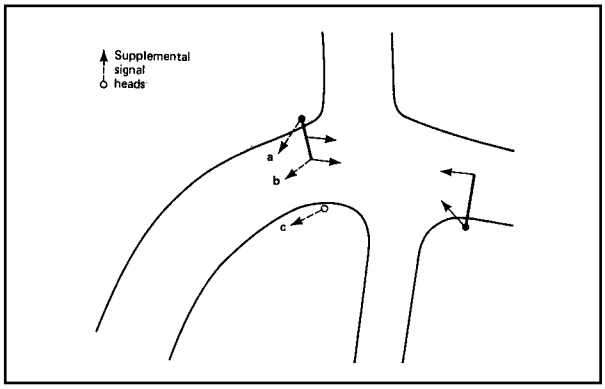

Figure 7–12: Signal Face Adjustments to Provide Adequate Sight Distance at Horizontal Curve
Source: 3

Figure 7–13: Supplemental Signal Faces Provide Improved Visibility for Curved Roadway Approach

7.5.4 Lens Size

The MUTCD provides guidance on when the use of 12-in. diameter signal lenses, rather than standard 8-in. signal lenses, is required. Local research has found that 12-in. lenses (especially the red lenses) are advantageous for increasing signal visibility and conspicuity at additional locations. An improvement project in Winston-Salem, NC involved replacement of existing 8-in. lenses with 12-in. lenses on at least one approach at 53 intersections. None of the locations had been substandard according to MUTCD criteria. The city reported a 45 percent reduction in targeted crashes.[12] Similarly, the use of a double red-signal display within a signal face is another method of increasing conspicuity. An evaluation of this treatment applied at nine locations in Winston-Salem[12] showed a 33 percent decrease in right-angle crashes.

7.5.5 Backplates

Backplates can be used to improve signal face conspicuity. Backplates are especially useful for signal faces mounted over the roadway because they increase the contrast between the signal display and the bright sky background, as illustrated in Figure 7–14. Also, for signals that are oriented in an east-west direction, backplates help to reduce the glare effect of the rising or setting sun. At six locations in Winston-Salem, NC, backplates were added on one or more approaches, resulting in a 52 percent reduction in right-angle crashes.[12]

Figure 7–14: Backplates Around Signal Faces Provide Improved Conspicuity Against the Sky Background

The MUTCD currently requires that backplates be a dull black color. However, it is anticipated that FHWA will likely give tentative permission for the addition of a white, retroreflective border around the edge of the backplate. This is similar to a treatment tried in Saanich, British Columbia where a yellow retroreflective border was added to the backplates at six intersections.[26] In the second and third years after installation, nighttime crashes decreased significantly from 14 per year to five and three crashes per year. Figure 7–15 illustrates the use of a white, retroreflective border on a signal backplate in the United Kingdom.

7.6 Removal of Traffic Control Signals

7.6.1 Effect on Safety and Efficiency

At some signalized intersections, traffic control signals may have been needed at one time but changing

Figure 7–15: White Retroreflective Border Added to Signal Backplate for Improved Nighttime Conspicuity

conditions have reduced this need. Many engineers are reluctant to attempt the removal of traffic signal control, fearing liability consequences. In reality, a reasonably analyzed and carefully documented decision to remove signal control can be a relatively low-risk action. It must be recognized, however, that the decision process must also include consideration of institutional and political issues in addition to an analysis of technical factors.

The impacts of signal removal were examined in a research study sponsored by FHWA.[18] At intersections converted to two-way stop control, three variables were found to have a significant impact on the crash experience after signal removal: adequacy of sight distance from the minor approaches, traffic volumes and crash frequency prior to signal removal.

The key research findings were as follows:

- Where signals were replaced with two-way stop control at intersections with inadequate corner sight distance, average annual crash frequency following signal removal rose dramatically (more than 135 percent). Annual average injury crashes doubled. Both increases can be fully attributed to the increased risk of right-angle crashes.
- Where signals were replaced with two-way stop control, higher volume intersections were associated with increased crash frequency following signal removal.
- Intersections with low crash frequencies prior to signal removal tended to have increased crash frequency after removal, and vice versa.
- At intersections with conditions favorable to all-way stop control (relatively balanced major and minor street traffic volumes), conversion from signals to all-way stop control resulted in a 62 percent reduction in annual injury crashes.

The city of Terre Haute, IN studied five intersections: two were converted to two-way stop and three were converted to all-way stop.[19] All of the intersections had entering traffic volumes in the range of 5,000 to 6,000 vehicles per day and all had signal installations that did not meet MUTCD warrants. Total intersection crashes were reduced from 21 to eight in 3-year before-and-after periods at the three intersections that were converted to all-way stop, with right-angle collisions representing the largest reduction. Total intersection crashes were reduced from 11 to nine at the two intersections converted to two-way stop, although right-angle crashes increased slightly.

7.6.2 Guidelines for Signal Removal

The FHWA document, *Criteria for Removing Traffic Signals*,[18] contains a recommended step-by-step procedure for signal removal involving site preparation, provision of advance notice to traveling

public, transition signal operations (for example, flashing) and post-removal monitoring.

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chapter eight

Designing and Operating Safer Roundabouts

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8.1 Introduction

Roundabouts have been the subject of great interest and attention in the United States since construction of the first "modern" roundabouts in the early 1990s. As of January 2004, there are an estimated 500 to 1,000 roundabouts in the United States. There are approximately 60,000 roundabouts worldwide, all built during the last 30 years. France started building roundabouts in the early 1980s and today has more than 20,000 roundabouts, the highest number for any country. In the United States there are four states with 50 to 100 roundabouts each (Colorado, Florida, Maryland and Washington), five states with 15 to 30 roundabouts (California, Kansas, Nevada, Oregon and Utah), six states with four to 10 roundabouts (Mississippi, New Jersey, New York, North Carolina, South Carolina and Vermont) and about 15 other states with three or fewer roundabouts.

Well-designed roundabouts can bring substantial benefits to transportation infrastructure. The purpose of this chapter is to explain the basic principles of roundabouts, key design elements and safety aspects.[*] It discusses the most critical roundabout design elements and performance methodologies, as well as those aspects of roundabouts that are seen as issues or have been the subject of diverging views.

Planners and engineers are encouraged to include roundabouts in their toolbox for intersection improvements. Whenever investments are considered for an intersection, roundabout feasibility and potential performance may be considered.

Numerous photographs are included in this chapter to illustrate concepts, not design details. Application of these concepts requires adherence to all federal and local design standards.

[*1] This chapter does not address all design elements for roundabouts. For that level of detail, the reader is referred to the *FHWA Informational Guide on Roundabouts*[2] or other state guides.

A glossary of roundabout terms is provided at the end of this chapter. The glossary also contains descriptions of different types of roundabouts, as well as illustrations of their differences from traffic-calming circles, rotaries and traffic circles.

8.2 Safety of Roundabouts

8.2.1 Vehicular Safety Statistics

Table 8–1 summarizes the latest safety statistics compiled for 33 roundabouts in the United States. These crash data were collected as part of a study[6] conducted in 2003 for the New York State Department of Transportation (NYSDOT), updating the safety study conducted for the Insurance Institute for Highway Safety (IIHS) in March 2000.[7] The NYSDOT study incorporated a more extensive database in terms of the number of intersections, years of data and diversity of conversions. Researchers compared the actual number of crashes after roundabout conversion to the number of crashes predicted under the empirical Bayes before-after procedure. This method is the accepted standard as per FHWA guidelines for conducting before-after observational safety studies and takes into consideration differences in traffic volumes before and after conversion.

As demonstrated by the data, roundabouts in the United States continue to show excellent safety statistics. Total crashes for all roundabouts combined decreased by 47 percent and injury crashes decreased by 72 percent in comparison to the condition predicted without a roundabout. For each of the four classifications of roundabouts studied, there were reductions in injury crashes ranging between 68 percent and 80 percent. Property-damage-only (PDO) crashes decreased for all categories except for the multi-lane urban roundabouts that had been converted from stop-controlled intersections (where no change in PDO crashes was observed).*

The NYSDOT study also identified five roundabouts (out of a total of 33) that showed an increase in crashes beyond the expected number of crashes. It is believed that these increases may be due to design compromises or to the addition of a new traffic generator at one of the approaches.

Table 8–1: Safety Effects of United States Roundabouts

Roundabout Characteristics Before Condition	# of Sites	Crashes Recorded after Roundabout			Crashes Expected without Roundabout			Percent Reduction in Crashes		
		Total	PDO	Injury	Total	PDO	Injury	Total	PDO	Injury
Single Lane, Urban Stop Controlled	12	40	35	5	130	105	25	69%	67%	80%
Single Lane, Rural Stop Controlled	9	72	54	18	204	148	56	65%	63%	68%
Multi Lane, Urban Stop Controlled	7	118	114	4	128	114	14	8%	0%	73%
Urban Signalized	5	91	86	5	143	124	19	37%	31%	75%
All Sites	33	321	289	32	605	490	115	47%	41%	72%

Source: 6

* The results are statistically significant at the 95 percent confidence level, except for the results shown for all accidents for the seven multi-lane roundabouts converted from urban stop controlled intersections. They showed a reduction of 8 percent for all crashes.

Comparing single-lane roundabouts to multi-lane roundabouts, the NYSDOT study shows that in terms of injury crash benefits, single-lane roundabouts are not more effective than multi-lane roundabouts. All types of roundabouts show reductions of injury crashes in the range of 68 percent to 80 percent. In terms of PDO crashes, single-lane roundabouts seem to be much more effective than multi-lane roundabouts. In multi-lane roundabouts there are additional side-swipe, entering-circulating and circulating-exiting conflicts and increased visibility obstructions. On a two-lane approach one entering vehicle may at certain moments block the view of another entering vehicle. Speeds also tend to be higher in multi-lane roundabouts, although not different enough to affect injury crashes, according to the NYSDOT study. It should be noted also that the higher numbers of crashes in multi-lane roundabouts are due to a large degree to the higher number of entering vehicles.

8.2.2 Pedestrian and Bicyclist Safety

The pedestrian and bicycle crash data available in the United States are too limited to draw statistically valid conclusions regarding pedestrian and cyclist safety in roundabouts. Not enough sites have significant pedestrian volumes and there are even fewer crashes involving pedestrians before-and-after conversion. However, the available data seem to point towards a reduction of pedestrian injuries and there is also anecdotal evidence that roundabouts can accommodate pedestrians in a safe manner.

For the 24 roundabouts studied in the IIHS study there were three reported pedestrian crashes in the before period and one with minimal injuries in the after period. The bicycle injuries changed from four in the before period to three in the after period. The two two-lane roundabouts built in urban areas with high pedestrian volumes (the Towson roundabout in Towson, MD opened in October 1998 and the Clearwater Beach Entry roundabout in Clearwater, FL opened in December 1999) have had a very good pedestrian safety record. The Towson roundabout had two pedestrian injuries in the 5 years prior to roundabout conversion and had one pedestrian injury in the 5 years after conversion. Prior to roundabout conversion, the Clearwater Beach intersection had one pedestrian injury every 7.5 months and one bike injury every 6 months. As of June 2003 there have been no pedestrian injuries since the roundabout conversion.

The NYSDOT study reports on a project performed in Howard, WI[8] where the installation of two roundabouts near a middle school and an elementary school changed the speed environment significantly. Prior to the construction of the roundabouts, the local sheriff's department had designated the highway fronting the middle school a hazardous area due to high speeds, thereby forcing the school district to bus kids across the road. This situation was expected to worsen when the new high school opened on campus in 2000. Many residents were initially opposed to roundabouts, arguing that they would not be able to handle the traffic volumes and that they would endanger children's lives. The performance of the two roundabouts surprised many as they effectively reduced speeds and crash rates. The reduction in crashes and injuries occurred in spite of the introduction of hundreds of inexperienced high-school drivers. Following the roundabout installation, students were again allowed to walk or bike to school.

A study undertaken by the Swedish National Road and Transport Research Institute (VTI) analyzed pedestrian and bicycle safety in 72 roundabouts in Sweden.[9] Researchers collected data on the crashes and injuries during a period of 4 years and counted the numbers of vehicles, cyclists and pedestrians passing through the roundabouts. At all 72

roundabouts, there were 67 reported crashes involving bicyclists, 58 of which resulted in injuries. At 52 of the roundabouts there were no accidents involving bicyclists and eight roundabouts accounted for 48 bicycle crashes. Table 8–2 compares the actual number of bicycle crashes and injuries observed (reported) at the roundabouts, to those predicted according to previous VTI studies for conventional intersections, including those controlled by signals. The predictions are based on the numbers of vehicles, bicycles and pedestrians passing through the roundabouts, and therefore do take into consideration the actual volumes of pedestrians and cyclists using the roundabouts. Table 8–2, as well as Table 8–3, show how roundabouts (measured by the observed number of accidents) differ from the conventional intersections (estimated by the predicted number of accidents) for a given situation.

The VTI study shows that in single-lane roundabouts, bicycle safety is slightly better (20 percent fewer injury crashes) than in conventional intersections (two-way stop controlled or signalized intersections). In single-lane roundabouts, serious bicyclist injuries are about half those in conventional intersections. However, cyclists do not fare well in two-lane roundabouts: total injuries are more than twice the injuries in conventional intersections. The additional injury crashes observed in two-lane roundabouts in comparison to conventional intersections are all light injury crashes.

Table 8–3 compares the observed pedestrian crashes at the 72 roundabouts with those predicted based on the number of vehicles and pedestrians. For two-lane roundabouts, pedestrian safety is close to that for conventional intersections (with possibly 10 percent

Table 8–2: Bicycle Crashes at Single-Lane and Two-Lane Roundabouts

					Observed Number of					Predicted Number of				
No. of lanes	No. of roundabouts	Vehicle per day, average	Cycles per day, average	No. of accident years	Accidents	Injury accidents	Fatalities	Serious injuries	Light injuries	Accidents	Injury accidents	Fatalities	Serious injuries	Light injuries
1 lane	58	11066	1075	163	28	24	0	5	19	35.7	30.2	0.1	9.6	19.5
≥ 2 lanes	14	23375	1397	53	39	34	0	5	29	19	16	0.3	5	9.9

Source: 9

Table 8–3: Pedestrian Crashes at Single-Lane and Two-Lane Roundabouts

					Observed Number of					Predicted Number of				
No. of lanes	No. of roundabouts	Vehicle per day, average	Pedestrians per day, average	No. of accident year	Accidents	Injury accidents	Fatalities	Serious injuries	Light injuries	Accidents	Injury accidents	Fatalities	Serious injuries	Light injuries
1 lane	58	11066	486	163	3	2	0	0	2	11.2	9.3	0	2.3	5.7
≥ 2 lanes	14	23375	1338	53	12	10	1	2	8	10.4	8.9	0.1	2.8	6

Source: 9

more injuries). However, single-lane roundabouts offer better pedestrian safety than conventional intersections. Pedestrian injuries in single-lane roundabouts were 78 percent lower than for conventional intersections. VTI reports that the most significant variable affecting pedestrian injuries is the speed of entering, circulating and exiting traffic. The number of injuries had a quadratic relationship with speed.

The United Kingdom was one of the first countries to collect significant crash data on roundabouts. The United Kingdom has a great variety of roundabouts since it has tried and tested many different designs for more than 40 years. Table 8–4 summarizes the pedestrian injury rates per 1 million pedestrians entering a roundabout, for various types and sizes of roundabouts. Note that the increase in injury rates for larger roundabouts is to a large degree due to the higher volumes of vehicles in those roundabouts. According to the British crash prediction model, the number of pedestrian injuries is proportional to the product of the number of pedestrians times the number of cars.

Table 8–4: UK Pedestrian Injury Rates

Type of Roundabout	Injury Rate/1,000,000 peds
Mini Roundabouts	0.31
Small Roundabouts	0.33
Conventional (2 lanes)	0.45
Large (2+ lanes)	0.72
Traffic Signals	0.67

Source: 10, 11

Studies in The Netherlands[1] showed that replacing ordinary intersections (mostly four-way intersections with prior stop control or signalization) with single-lane roundabouts decreased the bicycle and moped (light motorcycle) injuries by 44 to 73 percent. Separate cycle paths were found to be safest and the bicycle lane at the outer edge of the circulatory roadway was the least safe.

8.2.3 Reasons for Improved Safety

Several reasons are cited for the safety benefits attributed to roundabouts:

- All vehicles are forced to slow down when they enter and circulate through the roundabout. Traffic driving through signalized intersections is often twice as fast as through roundabouts.
- The number of conflict points is reduced in a roundabout. Figure 8–1 compares the vehicular conflicts in a four-way intersection versus a four-

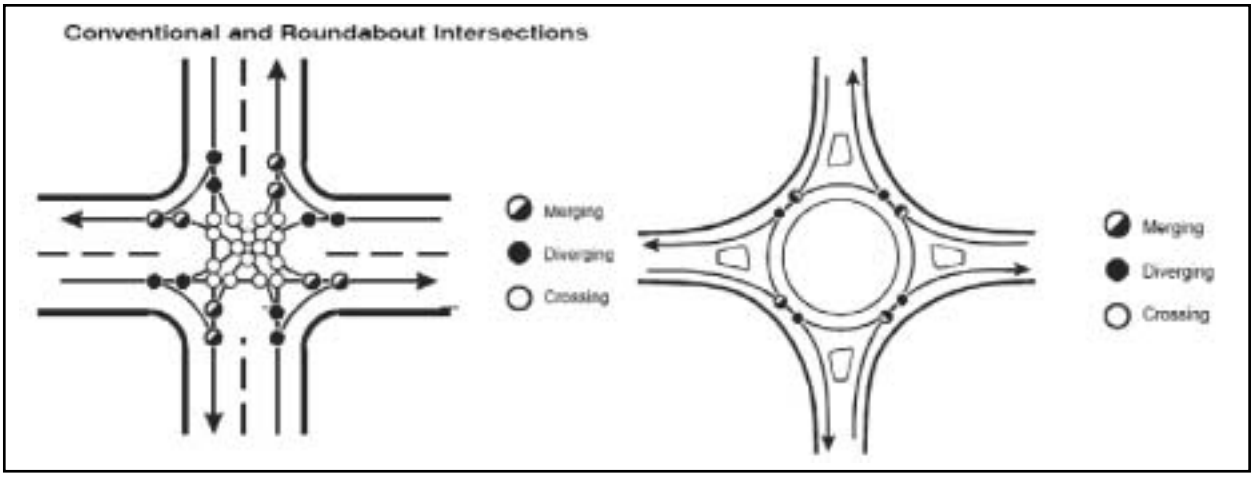

Figure 8–1: Comparing Traffic Conflict Points: Conventional Intersections Versus Roundabouts
Source: 2

leg roundabout. The roundabout has 75 percent fewer conflict points, but more importantly it has eliminated all crossing conflict points that result in the most severe right-angle or head-on crashes.

- The various conflict points in a roundabout are separated in time and space. A driver arriving at a roundabout first looks out for pedestrians, then concentrates on the merging conflict at the entrance, then on the diverging conflict at the exit and finally on the pedestrian crossing at the exit leg. In a four-way signalized intersection or stop-controlled intersection, drivers have to look out for several conflicts at the same time. The worst example of this is the driver trying to make a left turn against oncoming traffic and looking out for pedestrians crossing the side street.
- The last reason is the fact that drivers are asked to be attentive and pay attention at roundabouts. In signalized intersections the users receive simple and clear messages (green, red, walk, don't walk) and they associate this clarity with a high level of safety. Drivers sometimes accelerate to catch the green light and pedestrians often cross at the walk signal without paying attention. In a signalized intersection users get an exaggerated sense of safety, whereas in roundabouts they do not get the "road is yours" message and consequently behave in a more attentive and responsible manner. This tends to be true for all users.

Pedestrian safety in roundabouts is aided by low vehicular speeds and simplified conflicts.

- Pedestrians have to be concerned about one vehicular movement at a time when they cross the street and the splitter island allows them to cross in two phases.
- The narrower roadway approaches of roundabouts in comparison to conventional intersection approaches reduce the conflict area between vehicles and pedestrians.
- The location of the pedestrian crossings (typically one car length away from the outer circle) puts pedestrians at a location where pedestrians and drivers are more visible to each other, compared to the situation where the crossing is at the street corner and a driver makes a turn while looking out for other vehicles and pedestrians, and pedestrians sometimes have to look back over their shoulder to see right-turning vehicles.

These advantages are offset to some degree by the fact that pedestrians do not have a clear, guaranteed gap when they can cross a roundabout approach.

8.2.4 Types of Crashes in Roundabouts

Table 8–5 summarizes the types of collisions in roundabouts as reported in three international studies. The French data illustrate crash types for a sample of 202 injury crashes from 179 urban and suburban roundabouts for the period of 1984–1988.[12] Similar data from Queensland, Australia[13] and from the United Kingdom[10] have been added to the table. Figure 8–2 depicts the different collision types graphically. The frequency differences in types of crashes in the three studies may be due to different geometric features, driver behavior, traffic volumes and reporting methods in each country.

It can be seen that in all three cases the failure to yield at entry (leading to entering-circulating collisions) is by far the major cause of crashes, although the frequency of this type of crash varies substantially from one country to another. The UK statistics are for roundabout crashes prior to 1984. The percent of entering-circulating crashes has decreased to about 50 percent since then. The second most frequent type of crash in France and in the United Kingdom is the single-vehicle run off the circulatory roadway. Rear-end crashes are the second most frequent type in Australia, whereas they are third in the United Kingdom and fourth in France.

An assessment of the frequency of crash types indicates that the most effective countermeasure in most cases is the entry speed control. Lower approach and entry speeds will reduce the entering-circulating crashes, as well as the loss-of-control, single-vehicle crashes in the roundabout. Fixed objects should be

Table 8–5: Comparison of Collision Types at Roundabouts

Collision Type	France	Queensland (Australia)	United Kingdom[1]
1. Failure to yield at entry (entering-circulating)	36.6%	50.8%	71.1%
2. Single-vehicle run off the circulatory roadway	16.3%	10.4%	8.2%[2]
3. Single vehicle loss of control at entry	11.4%	5.2%	[2]
4. Rear-end at entry	7.4%	16.9%	7.0%[3]
5. Circulating-exiting	5.9%	6.5%	
6. Pedestrian on crosswalk	5.9%		3.5%[4]
7. Single vehicle loss of control at exit	2.5%	2.6%	[2]
8. Exiting-entering	2.5%		
9. Rear-end in circulatory roadway	0.5%	1.2%	
10. Rear-end at exit	1.0%	0.2%	
11. Passing a bicycle at entry	1.0%		
12. Passing a bicycle at exit	1.0%		
13. Weaving in circulatory roadway	2.5%	2.0%	
14. Wrong direction in circulatory roadway	1.0%		
15. Pedestrian on circulatory roadway	3.5%		[4]
16. Pedestrian at approach outside crosswalk	1.0%		[4]
Other collision types		2.4%	10.2%
Other sideswipe crashes		1.6%	

Notes:

1. Data are for "small" roundabouts (curbed central islands > 4 m [13 ft] diameter, relatively large ratio of inscribed circle diameter to central island size)
2. Reported findings do not distinguish among single-vehicle crashes.
3. Reported findings do not distinguish among approaching crashes.
4. Reported findings do not distinguish among pedestrian crashes.

Sources: France (CETUR 1992), Australia (Arndt 1998), United Kingdom (Maycock and Hall 1984

Source: 3/Kittelson & Associates

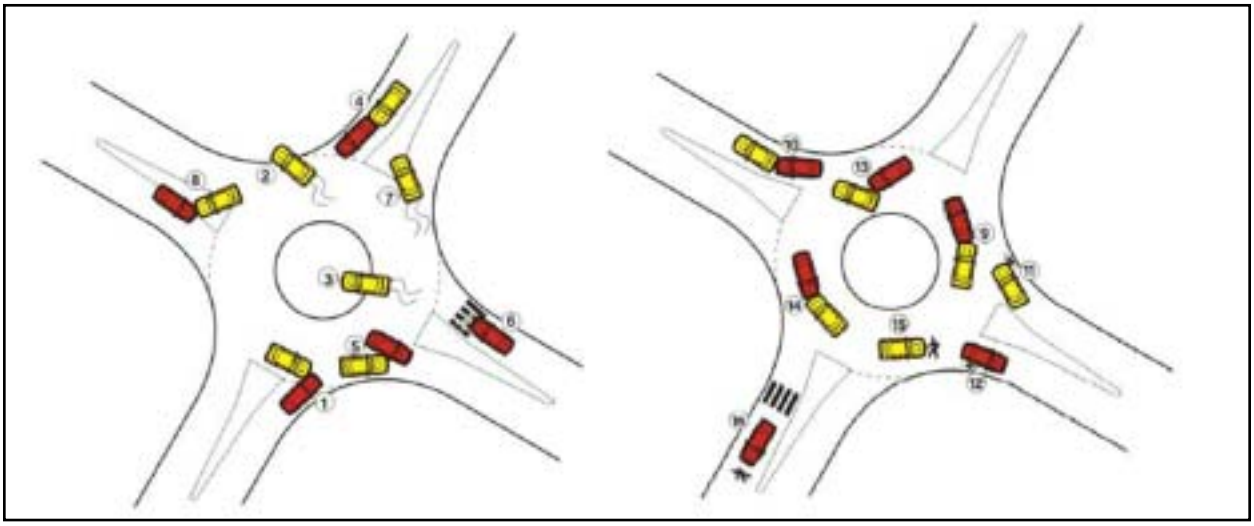

Figure 8–2: Diagram of Crash Types at Roundabouts
Source: 2

avoided in the paths of high speed movements. Clear zones around the central island need to be respected for sight distance reasons and to minimize severity of run-off-the-road crashes.

8.2.5 Geometric Variables Affecting Safety

Crash prediction models have been developed in the United Kingdom and Australia based on the vehicular crash experience in those two countries.[2] Crashes were analyzed by type of crash and related to the traffic flows and geometric variables of roundabouts. Although the model results may not be the same for U.S. conditions, these models are useful in explaining the relationship between various geometric or operational variables and resulting crash rates. The British model has crash prediction equations for five different types of crashes: 1) entry-circulating, 2) approaching, 3) single-vehicle, 4) other vehicle and 5) pedestrian. The following are the geometric variables (other than traffic or pedestrian volume variables) affecting the number of crashes:

- Entry width: doubling the entry width may increase injury crashes by maybe 20 to 30 percent, depending on the amount of circulating traffic.
- Circulatory width: widening the circulatory roadway by 6.5 ft. increases crashes by 5 percent.
- Entry path radius: a greater entry path radius (fastest path) increases entry-circulating crashes, but decreases single vehicle and approach collisions.
- Approach curvature: an approach curvature to the left is marginally safer than a straight approach.
- Angle between entries: a 90-degree angle between two consecutive entries is safer than a smaller angle. A double roundabout (two roundabouts side by side) will therefore be safer than a five- or six-leg roundabout.

Pedestrian crashes could only be related to the numbers of pedestrians and vehicles. No research effort has been able to relate the number of pedestrian injuries to any geometric variables.

The VTI study[9] reported that the ideal radii for the central island (including truck apron) were in the range of 33 to 82 ft. This would translate into inscribed circle diameters of about 105 to 215 ft. Smaller radii often lack deflection and larger ones result in higher circulating speeds.

8.2.6 Conclusions Regarding Safety

It is clear from the above statistics, as well as from other safety data from Europe and Australia, that well designed roundabouts offer significant safety benefits. Single-lane roundabouts, in particular, have shown to be very safe, not only for drivers but also for pedestrians and cyclists. Since a high proportion of all injuries and fatalities in the United States occur at intersections, substantial reductions in total crashes and injury crashes can be achieved by converting conventional intersections to roundabouts.

Given the significant difference in safety and ease of use between single-lane and multi-lane roundabouts, designers should be careful not to “overdesign” roundabouts by providing wider entries and more lanes than necessary. Such unnecessary features produce higher operating speeds, which are likely to increase collision potential. Where multi-lane roundabouts must be implemented to carry future traffic flows, phased construction should be considered, whereby the wider entries and circulatory roadway would only be built when volumes warrant them.

8.3 Delays and Capacities of Roundabouts

Capacities, delays and queue lengths can be calculated for each roundabout entry. The FHWA informational guide provides entry capacity charts for single-lane and two-lane roundabouts, based on a simplified roundabout design and British empirical equations. Practitioners should be aware that these charts reflect one single set of geometric variables and are not representative of all single-lane or two-lane roundabouts. The actual capacities may vary significantly depending on specific geometry.

The *Highway Capacity Manual*[14] provides a general gap-based formula with low and high estimates for gaps and follow-up times that allows the analyst to estimate entry capacities of single-lane roundabouts. This formula does not relate capacity to geometry. It is considered to be less reliable than those discussed in the FHWA guide.

The two methodologies described above exemplify the two approaches and types of software models used in the United States to estimate capacities. The British method uses an empirical regression approach based on actual measurements at congested roundabout entries, whereas the Australian method uses an analytical approach where capacity is estimated based on geometric and behavioral variables (critical gaps and follow-up headways). The circulating flow in front of the specific entrance and the entering flow are the major traffic variables in all models.

The software program used by the "analytical" designers is aaSIDRA (often referred to as SIDRA) and the software used by the "empirical" designers is either ARCADY or RODEL. Whereas aaSIDRA has the advantage that it can take into consideration behavioral differences between various regions and countries and can be "calibrated" based on gap measurements at similar adjacent roundabouts, it is not certain that the relationship between gaps and capacity is sufficiently predictable under all traffic conditions, especially the more extreme conditions. In ARCADY and RODEL (two separate software packages based on the same empirical equations) roundabout performance is directly related to a series of geometric variables. The relationship between geometry and performance is direct and makes these programs very design friendly. At this stage it is not known to what degree the capacity data collected in the United Kingdom is applicable to U.S. conditions today or in the future. More research is currently underway in the United States regarding the most appropriate methods. NCHRP Project 3-65 is collecting extensive operating, safety and geometric data on U.S. roundabouts.

Both software packages seem to be used more or less equally by the various jurisdictions and consultants in the United States. Comparing the user surveys undertaken in 1997[1] and in 2003[6] it seems that the use of the empirical model is catching up with the analytical model. Whereas some agencies require aaSIDRA for their roundabout analyses, others require the use of RODEL. To be on the safe side many jurisdictions and consultants use both capacity methods.

It should be noted that the two software packages may give significantly different results.

- For roundabouts with high circulating volumes, RODEL/ARCADY predict higher capacities than SIDRA.
- For roundabouts with low circulating volumes SIDRA predicts higher capacities than RODEL/ARCADY.
- SIDRA estimates single-lane entering capacities of about 1,950 vehicles when circulating traffic in front of that entrance is close to zero.

8.3.1 Geometric Variables Affecting Capacity

The British capacity method and performance models (RODEL and ARCADY) use the greater number of geometric variables to predict roundabout performance. Figure 8–3 shows the geometric variables that enter into British capacity calculations. The following defines the variables:

- Entry Width (e), measured from the right curb line, along a perpendicular line to the intersection of the left curb line (or edge line) and the yield line. This is a very important geometric variable affecting entry capacity.

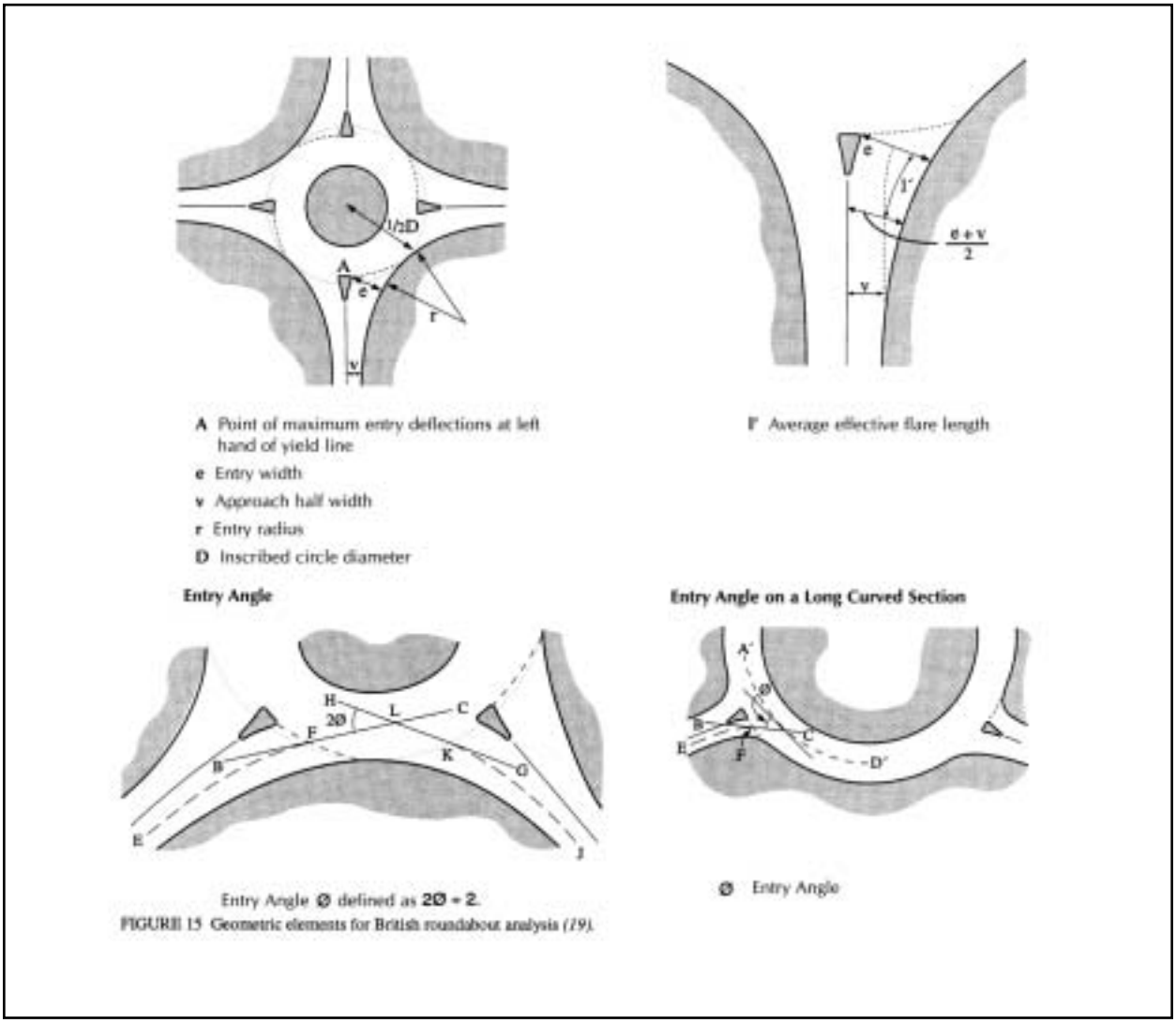

Figure 8–3: Geometric Variables Used in British Capacity Method
Source: 15/Leif Ourston

- Approach Half-Width (v), measured from the right curb line to the centerline or where there is a raised median, to the left edge line at a point upstream of the flare. This is also an important geometric variable affecting safety.
- Average Effective Flare Length (l') is the distance between the entry line (e) and the width line that has a width that is the average of the entry width (e) and approach half-width (v). See Figure 8–3. Based on these values the model calculates the sharpness of flare (S) measuring the rate at which extra width is added along the flare. A large value for S corresponds to short, severe flares and small values of S correspond to long, gradual widenings. According to the United Kingdom formula, flaring from one lane to two lanes over 100 meters gives about 95 percent of the capacity of a two-lane approach. With a 10 meter-long flare, the one-lane capacity can be increased by about 40 percent.
- Inscribed Circle Diameter (D) or ICD, is the diameter of the largest circle that can be inscribed within the intersection outline. With high circulating volumes, an increase of the ICD will augment capacity at all approaches.

- Entry Angle (Ø), is the conflict angle between entering traffic and circulating traffic. Figure 8–3 shows how to measure the entry angle. The entry angle has a moderate effect on capacity.
- Entry Radius (r), is the minimum radius of curvature of the right curb at entry. An entry radius greater than 20 meters has a small effect on capacity, however, smaller entry radii may reduce entry capacity significantly.

The Australian software aaSIDRA takes into consideration behavioral variables (critical gaps and follow-up headways), traffic bunching and a series of geometric variables, but does not include the approach half-width, entry radius and entry angle.

France, the country with the greatest number of roundabouts in the world, developed its own methods and software (Girabase). Similar to the British approach, it uses empirical regression equations developed on the basis of counts and measurements during 507 saturated periods of 5 to 10 minutes at 45 different roundabouts.[16] Girabase Version 3.0 (published in March 1992) takes the following parameters into consideration:

- Entry width;
- Width of circulating roadway;
- Radius of central island;
- Width of splitter island;
- Exit width;
- Angles between consecutive branches;
- Traffic flows (vehicles or passenger car equivalent);
- Pedestrian flows; and
- Roundabout environment (urban, suburban, rural).

Although the French approach is similar to the British approach, there are interesting differences:

- French researchers (as well as Swiss researchers) determined that the width of the splitter island along the inscribed circle affected the entry capacity. With wide splitter islands, entering drivers are less impeded by vehicles exiting at the same branch because the exiting vehicles have to diverge from the circulating stream earlier. With a splitter island width of less than 49 ft., part of the exiting traffic is included in the impeding traffic calculation.
- Swiss engineers determined a similar influence of exiting traffic on entry capacity. Here the exit traffic impedance is calculated on the basis of the circulatory distance between the diverge point and the merge point. When this distance is 92 ft. or greater, the influence of the exiting traffic vanishes.

It is not certain whether this variable is associative (the result of other geometric variables such as ICD, entry angle and entry radius) or causative.

8.3.2 Simple Rules of Thumb for Capacity Estimates

The FHWA informational guide provides a few simple "rules of thumb" regarding roundabout capacities.

- Circulating flows should not exceed 1,800 vehicles per hour (VPH) in a single-lane roundabout, and exit flows exceeding 1,200 VPH may need two-lane exits.
- French and Dutch engineers and planners use the rule of 1,500: when circulating plus entering traffic on one approach exceeds 1,500 VPH, a multi-lane roundabout may be needed.
- Total entering capacities for a single-lane roundabout are sometimes estimated at 2,500 VPH, and at 3,500 to 4,000 for a two-lane roundabout. These estimates are very rough numbers and can vary significantly according to the number of branches, geometry and traffic distribution. When traffic loads approach these volumes it is essential to verify the roundabout operation with a capacity model.

8.3.3 Delays

Shorter delays and queue lengths represent one of the major advantages cited for roundabouts as compared to other types of intersections.[1] The software programs mentioned earlier also provide estimates for average or maximum delays and queues. Queue lengths may be an important design criteria especially when the roundabout is located close to other intersections.

For pedestrians, the delays due to the physical geometry of the roundabout can be longer due to the greater walk distance.

8.4 Design Elements and Principles

This section explains basic roundabout design principles and describes the most important elements. The reader is referred to the FHWA informational guide, the Kansas guide, or other design guides for more detailed design questions. The emphasis of this section, as well as subsequent sections, is on the design procedures that have evolved during the last few years and have become the focus of discussions and research.

8.4.1 Speed Control

The basic design principle for roundabouts is the achievement of appropriate speeds through the roundabout. Roundabouts operate most safely and efficiently when geometry forces traffic to enter, circulate and exit at speeds between 15 and 30 mph and when speed differentials are minimized. The fastest vehicular path allowed by the geometry determines the design speed of the roundabout. The fastest paths must be drawn and verified for each entry and movement, including left turns, through movements and right turns, to verify that roundabouts do not allow excessive speeds. For through movements they are drawn, assuming a vehicle shifts from the left side of the entry lane toward the right-hand curb at the entry, then close to the central island, then close to the right-hand curb at the exit over to the left side of the exit lane.

Figure 8–4 shows the key movements through the roundabout, as well as different control radii. Figure 8–5 shows the fastest vehicular path for a through movement in a single-lane roundabout. In multi-lane roundabouts the verification of the fastest path should assume that vehicles cut across lanes and ignore lane markings. The more optimistic assumption of drivers staying within their own lane may underestimate roundabout speeds during off-peak periods.

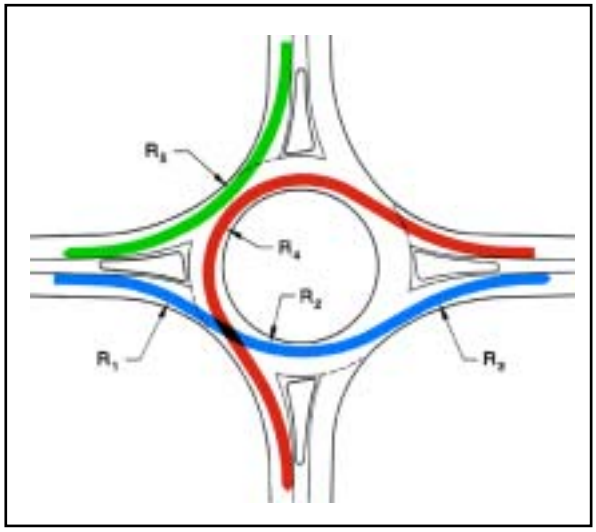

Figure 8–4: Vehicle Path Radii at a Roundabout
Source: 2

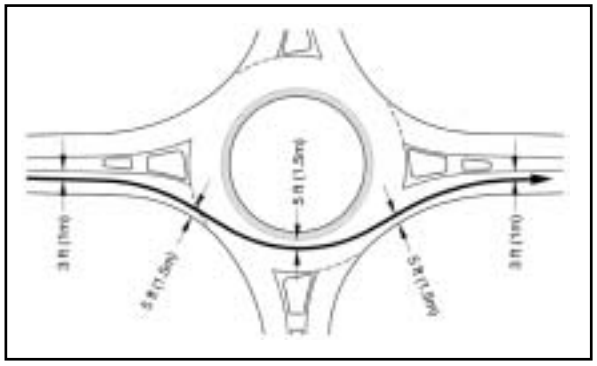

Figure 8–5: Fastest Vehicular Path through Single-Lane Roundabout
Source: 3/Kittelson & Associates

Table 8–6 shows the typical speeds used for roundabout entry design. The entry speed (R1) should generally be smaller than the circulating speed, which in turn should be smaller than the exit speed. This ensures that speeds will be at their lowest at entry, and reduces the likelihood of loss-of-control crashes in the

roundabout or exit. It also reduces the chances for back ups in the circulatory roadway. The relative differences between all speeds within roundabouts (the relative speeds between consecutive elements, and the relative speeds of the different traffic streams) should be minimized, preferably within a 6 mph range. Because this goal is sometimes difficult to achieve when designing for large trucks, speed differentials must sometimes be as large as 12 mph.

The design speeds shown in Table 8–6 for mini-roundabouts* and urban roundabouts are 5 mph higher than those shown in the FHWA guide. Maintaining design speeds in the 20 mph range makes the roundabout more bicycle and pedestrian friendly.

To guarantee low exit speeds for those legs with pedestrian activity, roundabout designers have sometimes recommended a reduced exit radius. Whereas restrictive exit speeds (exit speeds that are significantly lower than circulating speeds) may be acceptable in single-lane roundabouts with low volumes, this design approach should not be used in multi-lane roundabouts because it may lead to path overlap at the exit (illustrated later in Figure 8–7). Some exits at two-lane roundabouts had to be rebuilt because of this exit restriction and the resulting flow restriction and high number of crashes at the exit. Larger exit radii or even tangential exits are preferred to ease vehicle flow at the exit and reduce vehicle-to-vehicle conflicts.

Exit speed is in fact also controlled by the circulating radius and is generally no more than 3 to 5 mph higher than circulating speed. This suggests that reasonable exit speeds and a safe and friendly pedestrian crossing can be maintained even with large exit radii. Larger exit radii also improve visibility conditions of the pedestrians at the crossing. There are currently no available data relating pedestrian injuries to exit geometry. Until more data are compiled on this topic, it is prudent to provide sufficient exit curvature in the presence of pedestrians to prevent aggressive drivers from gaining excessive speed at the exit.

Table 8–6: Roundabout Design Speeds

Site Category	Maximum Entry (R_1) Design Speed
Mini Roundabout	20 mph (32 km/h)
Urban Compact Roundabout	20 mph (32 km/h)
Urban Single-Lane Roundabout	25 mph (40 km/h)
Rural Single-Lane Roundabout	25 mph (40 km/h)
Urban Double-Lane Roundabout	25 mph (40 km/h)
Rural Double-Lane Roundabout	30 mph (48 km/h)

Source: 3/Kittelson & Associates

* Note that the design speed for mini-roundabouts is not a real design speed since vehicles can drive over the mountable central island at higher speeds. This is why mini-roundabouts are only recommended in low-speed environments.

8.4.2 Approach Alignment

Aligning the centerline of the approaches with the center of the roundabout—the radial alignment design—has been presented as the preferred approach alignment in the FHWA and Kansas guides, because it assists in creating a balanced design in terms of entry and exit radii. Recent design philosophies have emphasized the advantages of the alignment offset to the left:

- Greater entry deflection and speed control, especially for small-diameter circles;
- Easier control of entry path overlap;
- Elimination of exit path overlap;
- Speed control of right-turn movements (R5); and
- Improved vehicle-pedestrian sight conditions.

The above advantages, in combination with the fact that exit speeds are controlled by the circulating radius, have led some designers to prefer the off-set to the left. Figure 8–6 is extracted from the FHWA guide but has different evaluative statements for the various alignments (as modified by this author): maximum deflection, average deflection and insufficient deflection. These alignment guidelines are most important for smaller ICDs, where speed control is more difficult. It should be noted that the overriding principle remains the speed control at entry. With a large ICD and central island diameter one could achieve speed control even with the offset to the right.

8.4.3 Design Vehicle

When designing roundabouts, consideration should be given to accommodating vehicles that can be reasonably anticipated. The choice of design vehicle depends on the roundabout location and functional classification of the intersecting roadways. However, unlike signalized intersections where the rare oversized truck may drive over opposing traffic lanes, roundabouts do not offer that flexibility. To protect landscaped areas, traffic signs and other intersection features, the roundabout designer must create a design that accommodates the rare oversized truck without damaging part of the roundabout. This design objective can make it difficult to maintain speed control through the roundabout. Mountable aprons around the central island, and possibly other

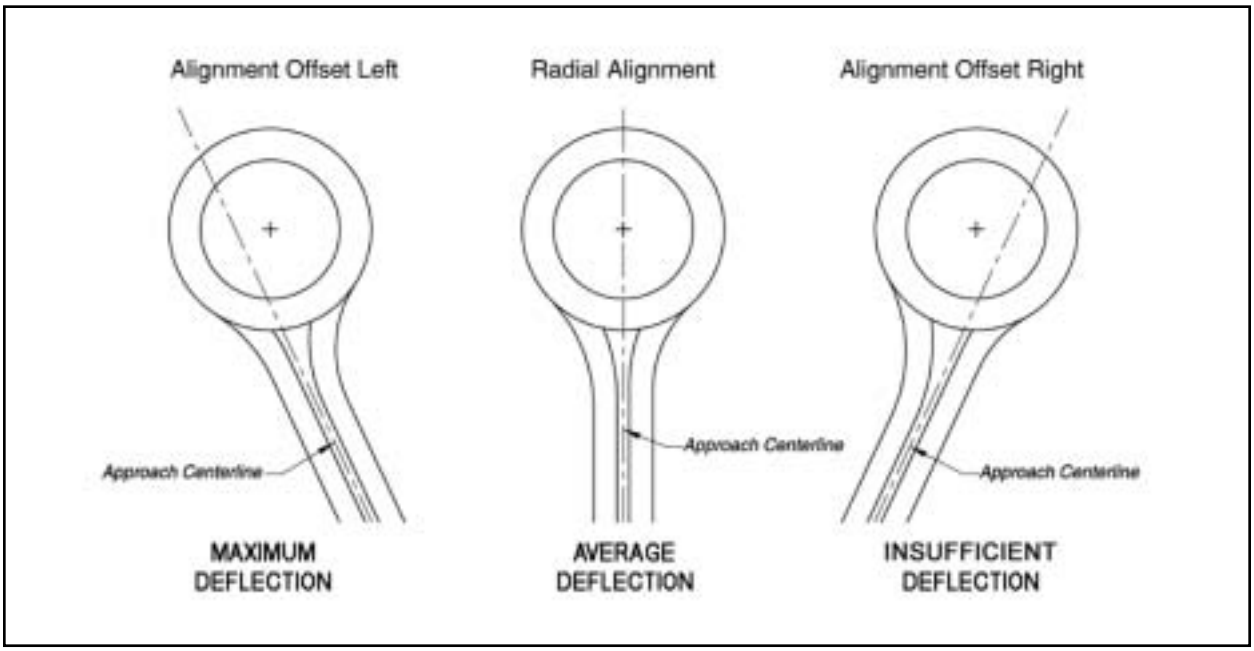

Figure 8–6: Approach Alignment Guidelines
Source: Adapted from 2

mountable areas in the entry and exit areas, may be used to accommodate large or very large vehicles without increasing speeds. These mountable aprons have to be solid enough to support heavy vehicles.

Typically designers determine the circulatory roadway width such that a city bus or school bus can circulate through the roundabout without using the apron. Any larger vehicles would need to use the truck apron. However, this design assumption needs to be verified in terms of its effect on entry and circulating speeds. If the ICD is very small the central island together with the truck apron may need to be widened and the circulatory roadway width may have to be narrowed to only allow passenger vehicles.

Emergency vehicles are included in the choice of design vehicle, with one key additional consideration: How is emergency access maintained in case of a blockage or crash in an entry or exit, or in case of maintenance work? One design choice is to assume that the emergency vehicle will use the opposite traffic routes (drive clockwise through part of the roundabout) similar to emergency vehicles in signalized intersections. Another option may be to design the splitter island curbs or other curbs such that they are mountable, thus allowing the emergency vehicle to pass the obstacle in the traffic lane. The choice depends on the traffic loads in the roundabout and on overall visibility across the central island.

8.4.4 Multi-Lane Design Challenges and Path Overlap

Multi-lane roundabouts pose an additional set of challenges related to the impacts of having two vehicles side-by-side approaching pedestrian crossings and circulating through the roundabout.

All roundabouts, with the possible exception of urban single-lane compact roundabouts, should be designed so that vehicles flow into and out of the roundabout along a natural, unconstrained path. This allows for smooth traffic flow, high capacity and safety. This design rule becomes more important in multi-lane roundabouts where traffic in one lane may be on a conflicting trajectory with traffic in the adjacent lane (Figure 8–7). Path overlap (defined here as conflicting trajectories, not as wheel path overlap)

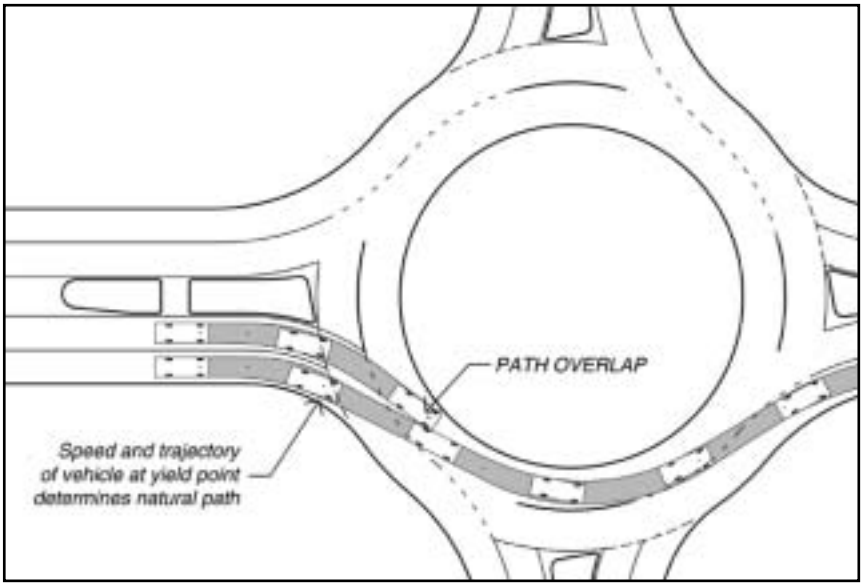

Figure 8–7: Path Overlap
Source: 3/Kittelson & Associates

is often caused by entry or exit radii that are too tight and results in lower capacity and higher crash rates. The FHWA and Kansas guides show design techniques to avoid the overlap of trajectories.

The Clearwater Beach entry roundabout that opened in December 1999 is located in an area with high pedestrian activity, particularly during spring breaks. One of the main design objectives for this roundabout was to guarantee low vehicular speeds to maximize pedestrian safety. Traffic calming was the overriding design principle, resulting in relatively narrow traffic lanes, and tight entry and exit radii. Figure 8–8 shows the original design of the Clearwater Beach entry roundabout.

The Clearwater Beach entry roundabout became a national news item, because of a high number of vehicular crashes (mostly fender benders) and limited capacity. Corrections have since been made to its entries, exits and striping. The photos in Figures 8–9 and 8–10 show the new pavement that was added to increase entry and exit radii and to widen some of the lanes. Circulatory striping changed from concentric striping to exit striping, forcing vehicles in the outer lane to exit at the high-volume exits (Figure 8–10). These design changes reduced the number of crashes from more than one per day to a few per year and increased capacity. The case of the Clearwater Beach Entry roundabout shows how relatively minor geometric changes can have a substantial impact on safety and capacity.

8.5 Signage and Markings

Signage and pavement markings are relatively simple for single-lane roundabouts. Issues and new design philosophies have arisen related to lane-control signage and lane markings in multi-lane roundabouts:

- Should we consider roundabouts as a series of consecutive T-intersections (where drivers are expected to change lanes between approaches), or as one single intersection (where drivers are expected to select a specific lane on each approach and stay in that lane throughout the roundabout)?
- Should roundabouts incorporate the same lane-use signs and markings as drivers are used to in signalized intersections, or should special signs

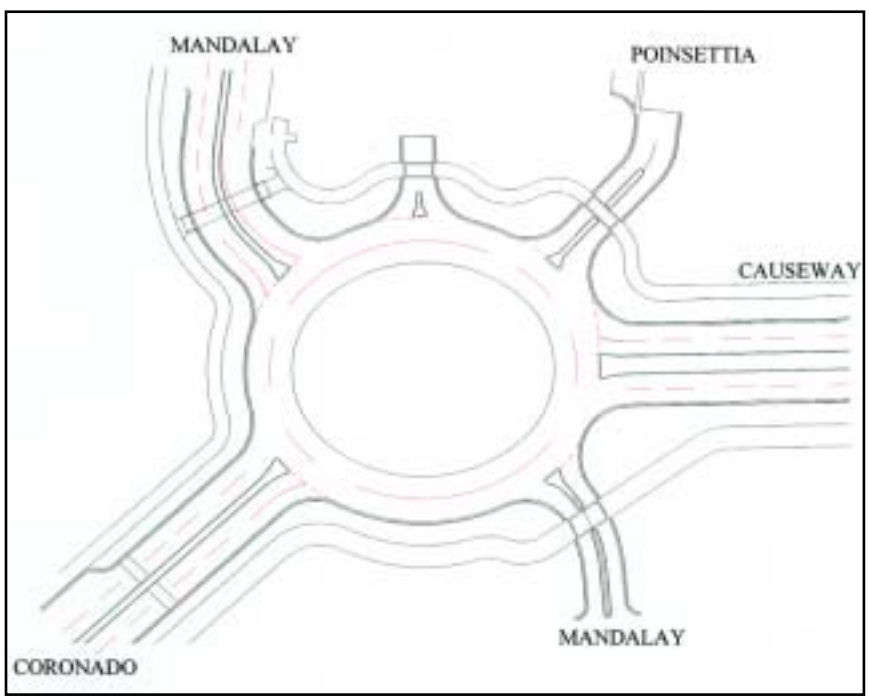

Figure 8–8: Clearwater Beach Entry Roundabout Original Design
Source: Rodel Software Ltd. for City of Clearwater

Figure 8–9: Increasing the Entry Width and Radius at Clearwater Beach Roundabout
Source: Lee A. Rodegerdts

Figure 8–10: Widening Exit Radius and Changing Striping at Clearwater Beach Roundabout
Source: Lee A. Rodegerdts

be developed that more closely reflect roundabout characteristics?

8.5.1 The MUTCD

The 2003 Edition of the MUTCD[17] does not include any special lane-use signs and markings for roundabouts. For consistency reasons, it recommends the lane-control signs and markings used for typical signalized or unsignalized intersections. Some jurisdictions, however, do not allow the use of a typical left-turn arrow at roundabout approaches (as shown for the pavement markings in Figure 8–11) because it could lead drivers to turn left after the

Figure 8–11: Example of Lane-Use Control Signs
Source: 3/Kittelson & Associates

splitter island. To alleviate this potential confusion, the use of straight arrows and straight/right-turn arrows have been used at the approaches, with the left-turn arrow only appearing in the circulatory roadway, as shown later in Figure 8–13. Alternatively, the pavement markings could be of the fish-hook type similar to the vertical signs in Figure 8–11, however, these signs are not included in the 2003 MUTCD.

8.5.2 Striping of the Circulatory Roadway

The FHWA informational guide suggests that, in general, lane lines should not be striped in circulatory roadways. This suggestion follows the recommendations and experience of the two countries with the largest number of roundabouts (France and United Kingdom). The underlying philosophies behind not striping the circulatory roadway are:

- Vehicles tend to take the shortest path through the roundabout anyway;
- Striping lanes for large trucks makes the roundabout larger and faster; and

- Rather than receiving too much clarity and guidance (and perhaps an exaggerated sense of safety), drivers should get the message that they should pay attention to other roundabout users.

Even in roundabouts that are striped, there is a significant percentage of vehicles cutting across lane markings. Striping for individual movements may also not be possible when traffic patterns change significantly between the different peak hours.

In contrast, recent trends in the United States* point toward the advantages of circulatory striping. Kinzel,[18] in his paper on signing and pavement markings for multi-lane roundabouts, introduces the subject as the "laissez-faire" approach versus the "positive guidance" approach. Striping the circulatory roadway brings clarity to the user, especially to the unfamiliar user who is accustomed to maximum clarity. Some roundabouts (the Clearwater Beach Entry roundabout is the most relevant example) have also benefited substantially from striping for exit movements. If designed to accommodate the different traffic loads, striping can help in guiding drivers to the right entry or exit lane and in optimizing roundabout capacity and safety.

Recent experience has also shown that concentric striping (with a concentric broken line separating the outer lane from the inner lane throughout the roundabout) is not an appropriate striping pattern. The concentric design views a roundabout as a series of intersections interconnected by the circulatory roadway, where drivers change lanes as needed in the roundabout. Exits would only be made from the outer lane. Whereas this may be the rule in some countries,

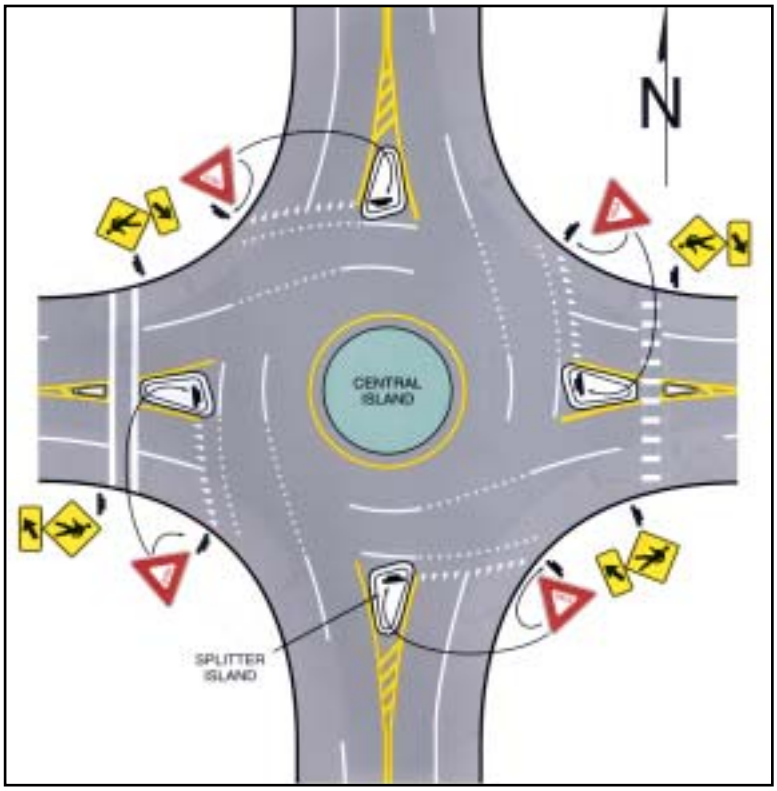

Figure 8–12: MUTCD Markings Example for Two-Lane Roundabout
Source: 17

* As exemplified by the Kansas design guide,[3] 2003 Edition of the MUTCD,[17] ongoing work by the MUTCD committee on roundabouts and research paper by Kinzel.[18]

it is not the view in the United States. The striping tendency in the United States has been towards spiral or exit striping, requiring vehicles in certain lanes to exit or to continue around the circle. Figure 8–12 represents the optional striping pattern* for two-lane roundabouts in the 2003 Edition of the MUTCD. Figure 8–13 shows a similar striping example for a roundabout with two minor approaches. Here the circulatory roadway varies in width to reflect the single-lane entries and exits for the minor streets. This pattern is only possible with striping that directs traffic in the outer lane to exit. This photo also shows a straight arrow in the left-hand lane of the approach because the designers did not want to suggest that one could make a left turn after the yield line. The left/straight arrow appears further downstream in the circulatory roadway. This type of marking is not supported by the 2003 MUTCD.

Figure 8–13: Example of Exit Striping at Griffis Air Force Base, New York
Source: NYSDOT

Figures 8–14 and 8–15 show striping examples for a two-lane roundabout with a double left-turn design, allowing one exit to be narrowed to one lane, and an

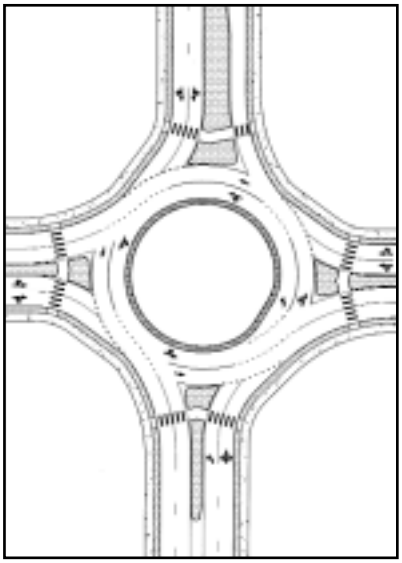

Figure 8–14: Schematic of Two-Lane Roundabout with Double Left-Turn Design
Source: Joel Marcuson

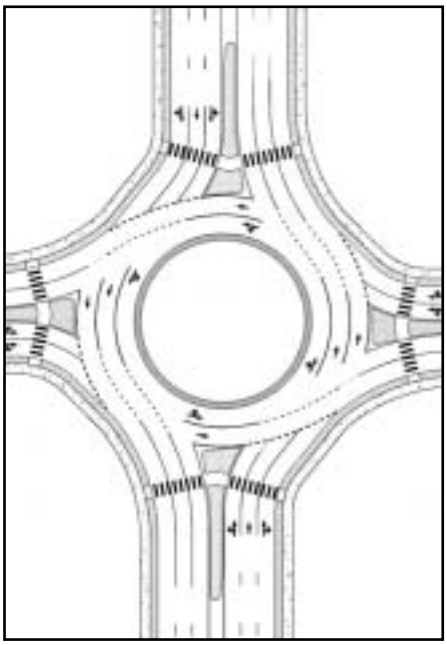

Figure 8–15: Schematic of Roundabout with Three-Lane Approach
Source: Joel Marcuson

* Even though the intent of this figure is to show signs and markings, it is not a good example of a roundabout. There is not sufficient deflection, pedestrian refuges are inadequate, there are no lane-use markings on the approaches and the two sets of lines at the entry may be confusing.

example with a major three-lane approach and a minor two-lane approach.

Based on the above experiences and recent trends in the United States, the following conclusions can be drawn:

- Striping multi-lane roundabouts for individual traffic movements may bring major safety and capacity advantages;
- Roundabout designers need to approach this subject with care and remain open to the arguments on both sides until more research can bring clearer conclusions;
- Further research should be undertaken on existing multi-lane roundabouts that are not striped to assess the effect of striping for individual movements;
- As for any other type of intersection, the lane configuration needs to be designed to accommodate the different peak-hour flows;
- Concentric striping should be avoided in multi-lane roundabouts; and
- If proper circulatory striping cannot be provided in a multi-lane roundabout due to very different traffic patterns throughout the day, or due to vehicle dimension constraints, it may be preferable not to stripe.

8.6 Designing Roundabouts for Pedestrians, Bicycles and Visually Impaired Users

Roundabouts can accommodate non-motorized users in a safe and efficient way. This section explains the key design features for these users.

Figure 8–16 shows the typical accommodations for pedestrians and bicyclists in a single-lane roundabout. These provisions would be similar in multi-lane roundabouts. The pedestrian crossing is at least one car length back from the yield line. The break in the splitter island remains at street level and needs to be large enough (a minimum of 6 ft. across the splitter island) to accommodate a pedestrian with a stroller or a wheelchair user. Pedestrian crossings should not be located adjacent to the yield or entry line. "Zebra-type" striping is generally recommended for these crossings. When located on local streets, the pedestrian crossings could be slightly raised to reinforce the need for motorists to slow down.

8.6.1 Bicyclists

Cyclists are the most vulnerable users of roundabouts. Safety data have shown that cyclists can be safe in single-lane roundabouts, but it is recognized that their safety is not as high in two-lane roundabouts. The

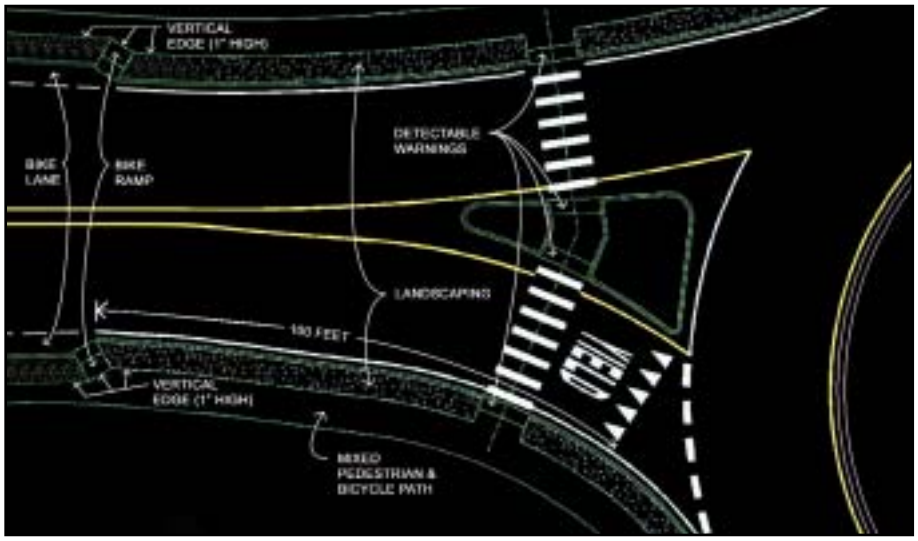

Figure 8–16: Typical Pedestrian Facilities at Single-Lane Roundabout
Source: 3/Kittelson & Associates

general approach in single-lane roundabouts has been to accommodate the cyclists in the same manner as regular traffic, and to assume that they will "claim the lane." This rule is facilitated by the low design speeds of the single-lane roundabout, putting the bicycles at a similar speed as vehicles. Less experienced cyclists are expected to dismount and walk through the roundabout using pedestrian crossings and paths. When bicycle lanes are provided on the approaches they should be terminated prior to the yield line to allow for merging with vehicles, or to allow a transition to an exclusive bike path or a shared bicycle and pedestrian path around the roundabout. Figure 8–16 shows this type of bicycle lane transition.

The photo in Figure 8–17 shows a different type of bicycle lane transition. In this application, the bike ramps must be constructed such that they cannot be mistaken for a pedestrian ramp by pedestrians with vision impairments. One way to avoid this potential confusion may be to insert a one inch high lip or curb at the separation between the walkway and the bike ramp with the bike ramp being higher than the walkway. This curb must be perpendicular to the bicycle travel path. Signing and pavement markings should be added to alert the bicyclist of the conflicts with pedestrians and of the shared usage of the pathway. Note that the ramp transitions in Figure 8–17 could easily be changed to accommodate this vertical lip at the separation between the walkway and the bike ramp. Also, in Figure 8–17 the raised circular flowerbed in the middle of the pathway on the left may be confusing to pedestrians with visual impairments. Such obstacles should be avoided.

Bicycle lanes must not be provided within the circulatory roadway (MUTCD 2003). When there are high bicycle flows, separate bike paths can be provided outside of the roundabout with bicycle crossings located parallel to the pedestrian crossings.

8.6.2 Pedestrians with Visual Impairments

Two concerns have been raised for visually impaired pedestrians at roundabouts: 1) how to provide cues around a roundabout to the crossing locations, to the crosswalk across the splitter island, and back to the sidewalk, and 2) how visually impaired pedestrians decide when to cross.

Figure 8–17: Alternative Accommodation for Bicyclists
Source: 3/Kittelson & Associates

Regarding the first issue, roundabouts are more complicated than typical intersections because pedestrians are asked to stray from the straight paths that they are used to at typical intersections. This concern can be addressed through the introduction of a raised edge along the walkway leading to the roundabout crossings and around the roundabout, as illustrated in Figure 8–18. This raised edge may be a few inches high or it could be several feet high. Introducing landscaped areas (possibly raised beds) between the walkway and the outer curb of the roundabout can achieve this objective. This will also prevent pedestrians from walking into the circulatory roadway and central island.

At the ramped pedestrian crossing itself, detectable warnings are required to alert the visually impaired pedestrian to the terminus of the sidewalk. Visually impaired pedestrians prefer to cross from one side of the street to the other side in a straight line across the splitter island. However, attention needs to be paid to the design of the ramps so that wheelchair users can approach them in a perpendicular manner and can maintain all four wheels on the pavement. Given the angular configuration of entry and exit curbs and the desire to maintain pedestrian ramps perpendicular to the curbs, with crossings as short as possible, a crossing design may need to be adopted with a directional break in the splitter island (as shown earlier in Figure 8–16). The break in direction should be in the middle of the splitter island as a cue to the pedestrian. Detectable warnings also need to be installed at the curb lines of the splitter island to alert visually impaired pedestrian of the splitter island location (Figures 8–18 and 8–19). The Draft Guidelines on Accessible Public Rights-of-Way[19] published by the U.S. Access Board recommend barriers (landscaping, railings, bollards with chains)

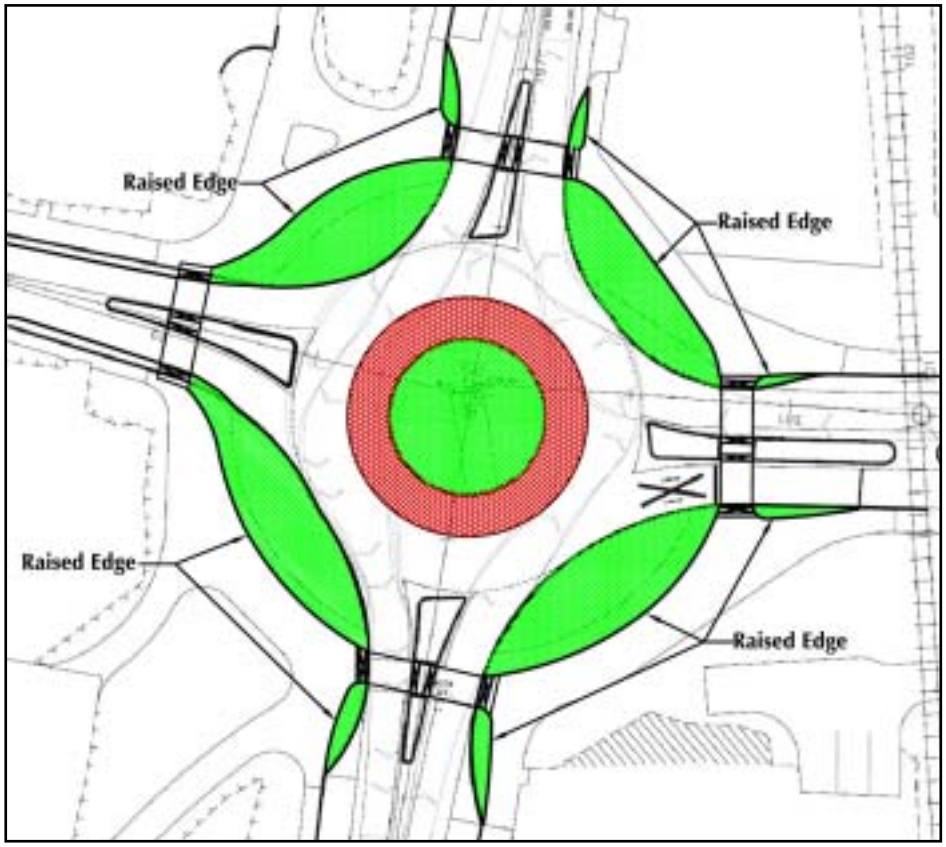

Figure 8–18: Example of Accessible Walkway
Source: Buckhurst Fish & Jacquemart

where pedestrian crossings are prohibited and raised truncated domes 0.2 in. high and aligned in a square grid as a detectable warning surface. The reader is referred to Chapter 4 for additional detail on general ADA requirements for pedestrian accessibility.

Figure 8–19: Pedestrian Crossing with Detectable Warnings
Source: 3/Kittelson & Associates

The second issue related to the crossing decision is more complicated. It is not so much an issue of actual safety as it is an issue of usability. Because pedestrian safety is largely a function of vehicle speed through the intersection, all pedestrians benefit from reduced vehicular speeds in roundabouts. They also benefit from shorter crossing distances. However, research conducted for the U.S. Access Board has shown that, at certain roundabouts, audible cues to gap availability of sufficient length to cross the street were not effective.[20] The decision to cross or not cross was perceived as hazardous whenever traffic volumes were high or there was substantial ambient noise (traffic or other noise) that made it impossible for the pedestrian to distinguish a vehicle exiting at the approach in question and to judge whether there was a gap long enough to cross. Based on the above research, the definition of accessibility for roundabouts has become synonymous with the ability to detect a gap that is long enough to cross to or from the splitter island to the curb—a guaranteed and recognizable gap.

The gap perception problem at roundabouts is not substantially different from that at busy signalized intersections where pedestrians cross concurrently with parallel traffic movements (signalized intersections without exclusive pedestrian phases). When traffic volumes and ambient noise are high in these signalized intersections, visually impaired pedestrians are in conflict with right- and left-turning traffic during the walk phase and cannot distinguish whether there is a crossing gap. Even though pedestrians with visual impairments can distinguish the beginning of the traffic phases, they cannot distinguish straight traffic movements from turning movements. The accessibility definition does not take into consideration other pedestrian behaviors or strategies, such as "claiming the lane" where pedestrians in low-speed environments walk into the crossing in a more assertive manner and assume that drivers will slow down or yield.* This behavior by pedestrians is very common in busy urban environments and is in response to the laws of many states that give the right-of-way to pedestrians only when they are in the crossing. Visually impaired pedestrians occasionally use a similar strategy by poking their cane into the traffic lane, thus in effect claiming the crossing and exerting their priority right. Leading pedestrian intervals introduced in signalized intersections (whereby pedestrians get a few seconds advance walk signal before vehicles get the green light) also do not provide a sufficient gap to cross the street. They merely position the pedestrians into the crossing and help them claim the crossing.

* The participants in the study for visually impaired pedestrians were instructed to assume that vehicular traffic would not yield to them.

To provide a recognizable gap long enough to cross to or from the splitter island, the Draft Guidelines on Accessible Public Rights-of-Way recommend the installation of pedestrian activated traffic signals for each segment of the crosswalk. A comprehensive research study (NCHRP 3-78) will look at the usability of roundabouts and slip lanes by pedestrians with visual impairments and will evaluate alternative accessibility options.

8.7 Particular Examples and Applications

Roundabouts have been used in a wide range of applications: low-volume traffic calming situations, high-volume situations where roundabouts are alternatives to signalization, urban environments with significant pedestrian circulation and rural environments. It is worth noting some of the particular characteristics of roundabouts that explain several unexpected applications.

Short delays and queues: Because of their shorter queues, roundabouts can be constructed close to other intersections or even close to other roundabouts. Two-roundabout intersections have been built in locations where several roads meet at acute angles within a certain distance. Instead of building one large roundabout, two roundabouts side-by-side or with a short link in between often can fit better into the available right-of-way. Attention needs to be paid to the queuing calculation to make sure that one roundabout does not block the other roundabout. This configuration is often feasible because the traffic volumes flowing between the two legs on either side of the acute angle are generally low. Figure 8–20 shows an example of a two-roundabout intersection in a highly urbanized environment in the City of Lausanne, Switzerland.

Wide Nodes and Narrow Links: Roundabouts are sometimes referred to as wide nodes and narrow links, because unlike traffic signals they can increase the capacity of an intersection without widening the approaches. Signalization often requires roads to be widened to provide the necessary lane capacity at the approach and downstream from the signal. This particular characteristic makes roundabouts particularly beneficial for situations where the approach roads cannot be widened or where it is very expensive to widen them. Examples include intersections near overpasses, underpasses, or adjacent to historically important buildings or ecologically sensitive lands. For example, the NYSDOT opted for a roundabout solution to increase the capacity of a rural arterial adjacent to a critical watershed area in Westchester County because that option did not require widening the highway.

Two-roundabout interchanges with one overpass or underpass over the freeway are a direct consequence

Figure 8–20: Two-Roundabout Intersection in Lausanne, Switzerland
Source: Buckhurst Fish & Jacquemart

of this characteristic. For existing interchanges, the two-roundabout design increases the interchange capacity without widening the overpass or underpass. Figure 8–21 shows the first two-roundabout interchange built in the United States. The cost for this interchange improvement was one-quarter of the estimated cost for the signalization alternative. Similarly, for new freeway interchanges the two-roundabout configuration can reduce the construction costs significantly because of the smaller overpass or underpass. Roundabouts are also very appropriate for these types of applications because of shorter queues.

Figure 8–21: Two-Roundabout Interchange in Vail, CO
Source: Washington Group International

As can be seen on the far side of Figure 8–21, two-roundabout interchanges in a diamond shape may also allow the central islands to become raindrop islands if the circulation to and from the freeway ramps is in a one-way direction. This layout maintains maximum fluidity under or over the freeway.

Easy U-Turns: Roundabouts are an elegant solution for U-turns, making them ideal intersections along commercial strips. They can also become part of a very effective access management program, whereby a series of roundabouts along a commercial arterial allow the elimination of all left turns through the construction of a raised median between the roundabouts. All left turns are then replaced by U-turns around the roundabouts. Such access management schemes have been successful in Avon and Golden, CO.

Flexibility in Design of Central Island: Making the central island mountable can shrink the size of the roundabout significantly and facilitates the construction of mini-roundabouts in restricted residential or commercial areas. Mini-roundabouts function in the same manner as standard roundabouts, except that the larger vehicles drive over the central island. Figure 8–22 shows an example of a mini-roundabout in a constricted area in the historical part of Lausanne, Switzerland.

Figure 8–22: Mini-Roundabout in the Old Lausanne, Switzerland
Source: Buckhurst Fish & Jacquemart

8.8 Conclusions and Lessons Learned

Roundabouts have been shown to be effective tools to improve traffic safety and efficiency at intersections. Traffic planners and engineers may include roundabouts whenever they consider options for a

new intersection or for improvement to an existing intersection.

The literature referenced in this chapter espouse that roundabouts are appropriate under a wide variety of conditions, including the following:

- Unusual geometry (for example, Y-intersections, acute-angle, intersections with more than four legs, a pair of closely spaced intersections);
- Character or speed of the road changes (for example, at entry points to a community, where posted speed limits change or at junctions where a bypass road connects to an arterial);
- Important from an urban design or visual point of view (as long as the basic engineering and safety criteria can be satisfied);
- High left-turn flows or changing traffic patterns;
- U-turns are frequent or desirable, perhaps in conjunction with access management strategies (for example, raised median) along commercial corridors;
- High crash rates, especially locations with a high number of accidents related to cross movements or left-turn or right-turn movements;
- Traffic signals are not warranted or where a four-way stop is being considered (or has been installed);
- Storage capacities for signalized intersections are restricted or where the queues created by signalized intersections cause operational or safety problems (for example, at diamond interchanges or intersections near rail underpasses, bridges and tunnels);
- Along congested arterials, in lieu of full-length road widening;
- Cross-street visibility restrictions; and
- Along roadways with historical problems of excessive speeds.

Several conditions are commonly mentioned as typically inappropriate for a roundabout application. However, as noted below (and as is typical for conventional intersections as well), the factors that make a particular design workable are more complex than can be conveyed in a simple phrase.

- **Locations where there is insufficient space for an acceptable outside diameter**—Single-lane roundabouts generally consume more space than equivalent signalized intersections at the junction itself but their approaches are often narrower. Multi-lane roundabouts compare more favorably in terms of space consumption.
- **Locations where it would be difficult to provide a flat plateau for roundabout construction**—Most guides recommend maximum grades of 3 to 5 percent depending on design speed. However, there are successful roundabouts with steeper grades.
- **Locations within a coordinated signal network because the roundabout would disrupt the platoons**—Although the disruption of platoons may be a problem, other benefits could be derived from the introduction of a roundabout in a signalized corridor. For example, if there is an intersection with a high left-turn movement, a roundabout may bring increased capacity to that intersection and may allow the two remaining segments of the corridor to be better optimized to different cycle times. Another example, at intersections where two synchronized corridors intersect or at triangular locations, the introduction of a roundabout may assist in untangling the conflicting phasing schemes.
- **Locations with heavy flows on the major road and light flows on the minor road**—A roundabout with a heavy flow on the major road and light flow on the side street can function with short delays because the high volume entry tends to have low conflicting flows (generated by the side street or opposing left turns). The capacity may be lower for side street entries, but this may be offset by the low traffic demand on the side street. The presence of a few left-turning vehicles from the major flow may create sufficient gaps for the side street entry. The traffic analyst needs to verify the capacities and delays for each approach before concluding that the

unbalanced flows reduce the efficiency of the roundabout.

- **Presence of numerous bicycles or pedestrians**—These can be addressed through special design features such as separate bicycle paths, zebra striping, pedestrian underpasses or pedestrian-activated signals further away from the roundabout (refer to Section 6.1 of this chapter).
- **Presence of visually impaired pedestrians**—Provision of special surface treatment must be considered to provide cues to the pedestrians with visual impairments. Pedestrian activated signals with audible messages may be considered (refer to Section 6.1 of this chapter).
- **Large proportion of heavy vehicles**—Roundabouts like any other intersection type may need special treatment for high percentages of heavy vehicles, such as more generous dimensions.
- **Presence of a fire station**—Similar design precautions are taken as with signalized intersections. Special signals can be set up.
- **Presence of a rail crossing**—Similar precautions are taken as for other intersections. After the train passed, the roundabout may allow a faster return to normality as compared to other types of intersections.
- **Junction located at the top or bottom of a grade**—If the sight distances at the approaches are not adequate, special advance signs or signals need to be installed.
- **Proximity of adjacent signals**—Undisciplined drivers may block a roundabout in a similar manner as at a signalized intersection.

Because roundabouts are still relatively new in many areas, the government agency building them may undertake a public education and information campaign prior to opening the roundabout. This campaign should explain the advantages of the roundabout and driving rules. The FHWA informational guide and the Kansas guide include examples of educational brochures.

Finally, the design of a roundabout should recognize special local characteristics. Roundabout design is performance-based design (not code-based or warrant-based) and requires considerable engineering judgment. The FHWA informational guide refers to this in its foreword: "Since there is no absolutely optimum design, this guide is not intended as an inflexible 'rule book,' but rather attempts to explain some principles of good design and indicate potential tradeoffs. In this respect, the 'design space' consists of performance evaluation models and design principles such as those provided in this guide, combined with the expert heuristic knowledge of a designer. Adherence to these principles still does not ensure good design, which remains the responsibility of the designer."

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Software Resources

1. aaSIDRA (known as SIDRA) available through
   McTrans Center 800-226-1013
   www.aatraffic.com/SIDRA

2. RODEL available from R. B. Crown
   Rodel Software Ltd.
   Highways House, Riverway
   Stafford
   ST163TJ
   United Kingdom
   Tel: 011 44 1782 599313
   Fax: 011 44 1782 316 388
   RSLcrown@aol.com

3. ARCADY
   Systematica North America
   PO Box 313
   Mt. Vernon, VA 22121
   Tel: 800-874-7710
   Fax: 703-780-7874

4. GIRABASE
   CETE OUEST
   Division Sécurité et Techniques Routières
   MAN – rue René Viviani
   BP 46 223
   44262 Nantes cedex 2
   France
   Tel: 011 332 40 12 85 01
   Fax: 011 332 40 12 84 44

Glossary

Elements of Roundabouts

This glossary follows the descriptions of roundabout elements and categories in the FHWA informational guide[2] and Kansas roundabout guide.[3]

Roundabouts are circular intersections defined by two basic traffic control and geometric characteristics:

- Yield control at all entries; and
- Appropriate geometric features to promote slow and consistent speeds for all movements.

Appropriate geometric features slow down traffic by deflecting entering, circulating and exiting traffic. Other principles apply to roundabouts: Parking is not allowed in the circulatory roadway and no pedestrians are allowed in the central island.

Some of the key roundabout features include (Figure 8–23):

Central Island: The center island is a raised area in the center of the roundabout around which traffic circulates.

Splitter Island: The splitter island is a raised area on the roundabout approach used to separate entering traffic from exiting traffic, deflect entering traffic away from the central island and provide waiting space for pedestrians crossing the approach in two stages.

Circulatory Roadway: The circulatory roadway is the path used by vehicles to travel in a counterclockwise manner around the central island.

Truck Apron: When the inscribed circle diameter (ICD) and circulating roadway are too small to accommodate trucks, a mountable truck apron is introduced on the central island, adjacent to the circulatory roadway, to accommodate the wheel tracking of large vehicles. Truck aprons should be sufficiently raised above the regular pavement to discourage motorists in passenger cars from cutting across the apron (at higher than the desired through speeds).

Yield Line: Entering vehicles must yield to circulating traffic coming from the left before crossing the yield line. The FHWA guide shows the yield line as a broken white line 12 in. wide located along the inscribed circle. Alternatively it suggests a "shark's teeth" line along that same line. The 2003 MUTCD includes a dotted line identifying the edge of the inscribed circle plus a "shark's teeth" yield line set back from the dotted line. In Figure 8–23, the yield line is denoted the "entrance line."

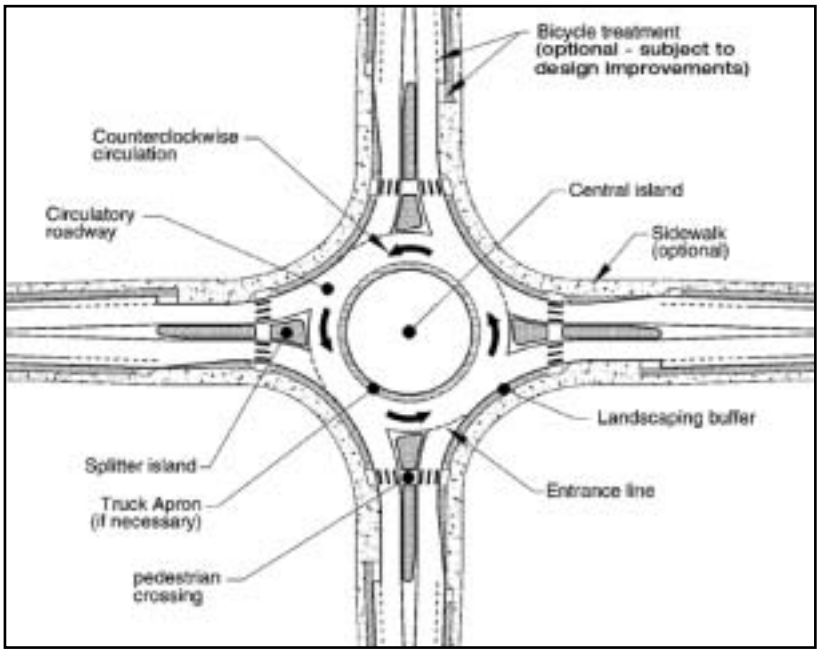

Figure 8–23: Roundabout Features
Source: 3/Kittelson & Associates

Pedestrian Crossings: Accessible pedestrian crossings are required at roundabouts where pedestrian facilities are provided. The crossing location is set back a minimum of one car length from the yield line, and the splitter island is cut to allow pedestrians, strollers, wheelchairs and bicycles to pass through and provide a refuge for users to cross in two phases. Some practitioners recommend against painting pedestrian crossings when pedestrian flows are less than 50 pedestrians per hour. Detailed accessibility elements are addressed in Section 8.6.

Bicycle Treatments: Bicyclists at roundabouts are given the option of traveling through the roundabout either as a vehicle or as a pedestrian, depending on the bicyclist's level of comfort. When there is a lot of bicycle traffic, the safest solution is to provide a separate bicycle path around the roundabout. Bicycle lanes are not recommended in the circulatory roadway. When bicyclists use the traffic lane, the entry lane width should be such that overtaking is minimized. Section 8-6 discusses the design details of the bicycle lane transition to the roundabout.

Landscaping Buffer: Landscaping buffers are provided at most roundabouts to separate vehicular traffic from pedestrian traffic, encourage pedestrians to cross only at the designated crossings and improve the aesthetics of the intersection.

Roundabout Categories

The FHWA informational guide and the Kansas guide have categorized roundabouts according to size, traffic volume and environment to differentiate design and operational characteristics. Note that there are small differences between the two guides reflecting a certain evolution in knowledge and understanding of roundabouts since the FHWA informational guide was published. For instance, the Kansas guide shows higher design speeds (higher by 5 mph) for the mini, urban compact and urban single-lane roundabouts, as compared to the FHWA guide. Also, both the FHWA and the Kansas guides refer only to single-lane and two-lane roundabouts. Because there are a significant number of roundabouts with more than two lanes, the list below takes into consideration the possibility of higher capacity roundabouts. The descriptions below reflect the general characteristics of the categories as suggested in the Kansas guide and as understood by experienced roundabout designers.

Mini-roundabouts: These roundabouts are small and are typically used in built-up environments with restricted right-of-way and lower speed environments (speeds of 30 mph or less on approaching streets). Because of its smaller size, the central island is fully mountable, allowing larger vehicles to circulate over the central island in a counterclockwise manner. Passenger cars circulate around the mountable central island. Mini-roundabouts are easy to retrofit into existing intersections, making them a cost-effective application. Mini-roundabouts can be single-lane or multi-lane. Their inscribed circle diameter (ICD) is in the range of 45 to 95 ft.

Urban Compact Roundabouts: These are characterized by their relatively small ICD, typically 100 to 120 ft., and by traffic volumes well below typical capacities of single-lane roundabouts. With almost perpendicular entries and exits, these are appropriate for local and residential streets. They are typically designed for a maximum speed of 20 mph.

Urban Single-Lane Roundabouts: With single-lane entries and one circulatory lane, this roundabout is similar to the urban compact roundabout, although it is designed for higher traffic volumes. Greater fluidity is achieved through a larger ICD of 110 to 150 ft., which also helps with the deflection. This roundabout is designed to achieve consistent entering and circulating speeds, typically a maximum speed of 25 mph.

Urban Multi-Lane Roundabouts: These have at least one entry with two or more lanes and a wider circulatory roadway, and are designed for higher traffic volumes. Speed control at entry and for circulating vehicles is critical. Typically the ICD is in

the range of 140 to 300 ft. They are designed for a maximum speed of 25 mph.

Rural Single-Lane and Multi-Lane Roundabouts: Rural roundabouts differ from urban roundabouts since they are often designed for higher speeds (up to 30 mph) with larger ICDs. Depending on their environment, they may include only a cut in the splitter island to accommodate pedestrian crossings (even if there are no adjacent sidewalks). In an area where no pedestrians are expected, rural roundabouts have no pedestrian features. Because they are often located in higher speed environments, such roundabouts may have traffic control devices to warn drivers or geometric features that assist in controlling approach speeds.

Traffic Circles

Traffic circles are often referred to as roundabouts, but in fact they do not satisfy the roundabout principles. The most frequent features violating roundabout principles are:

- Stop signs or traffic signals at the entry (note that traffic lights have occasionally been used to meter entering traffic on high-volume approaches at older and larger roundabouts in the United Kingdom);
- Parking in the circulatory roadway;
- Entering traffic merging with circulating traffic;
- Tangential entries and lack of speed control;
- Large vehicles allowed to turn clockwise through the circle;
- Priority given to entering traffic; and
- Pedestrians walking to the central island.

The following are recognized types of non-conforming traffic circles:

Traffic-calming circles: These are similar to single-lane mini-roundabouts except that they have small central islands that are raised rather than being mountable (Figure 8–24). Larger vehicles such as school buses or moving trucks may have to turn clockwise to make a left turn.

Rotaries: Often seen on the East Coast, they are designed for weaving movements with large diameters, long distances between consecutive

Figure 8–24: Typical Traffic Calming Circle
Source: 3/Kittelson & Associates

entries and exits, and high speeds. Figure 8–25 shows several older rotary designs.

Traffic Circles: These include a very large array of circular intersections including many circles still existing throughout the United States, some with traffic signals or stop signs at the entry and some with no entry controls (often with tangential high-speed entries).

Some of the more famous traffic circles include:

- Dupont Circle in Washington, DC (pedestrians in the central island, traffic signal control at the entrances and in the circulatory roadway);
- Columbus Circle in New York City (same reasons as for Dupont Circle); and
- Place De Gaulle at the Arc de Triomphe (formerly known as Place de l'Etoile) in Paris (entering traffic has the right-of-way).

Figure 8–26 shows the conversion of the old Los Alamitos traffic circle in Long Beach, California to roundabout operation, together with the main geometric changes. The principal changes involved yield-at-entry, reduced entry radii and additional entry lanes. Because of the natural features in the central island, the designers decided to maintain the large ICD of the original traffic circle (470 ft.). The resulting circulating speed was therefore higher (32 mph) than recommended, and consequently the reduction in crashes was not as significant as with other conversions. Total crashes decreased by 36 percent and injury crashes by 20 percent. In 1994 this roundabout carried total peak-hour volumes of 4,700 vehicles at levels of service A or B.5 Prior to conversion it operated at level of service F. It is one of two roundabouts in the United States with a four-lane approach.

Figure 8–27 is an aerial photo of the Kingston, NY circle taken a few weeks before it opened as a roundabout, showing the old and the new. The roundabout was built in the central island of the old circle. The ICD was reduced from 660 to 220 ft. The roundabout has three bypass lanes increasing the capacity of the two-lane roundabout. The old pavement of the traffic circle became the base for the multi-purpose path circulating around the roundabout.

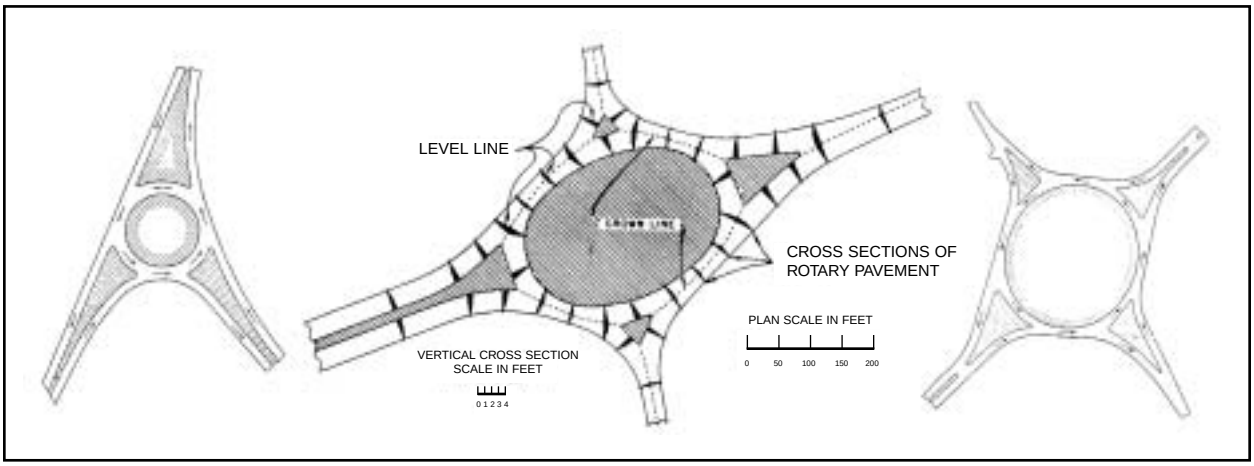

Figure 8–25: Old Rotary Designs
Source: 4

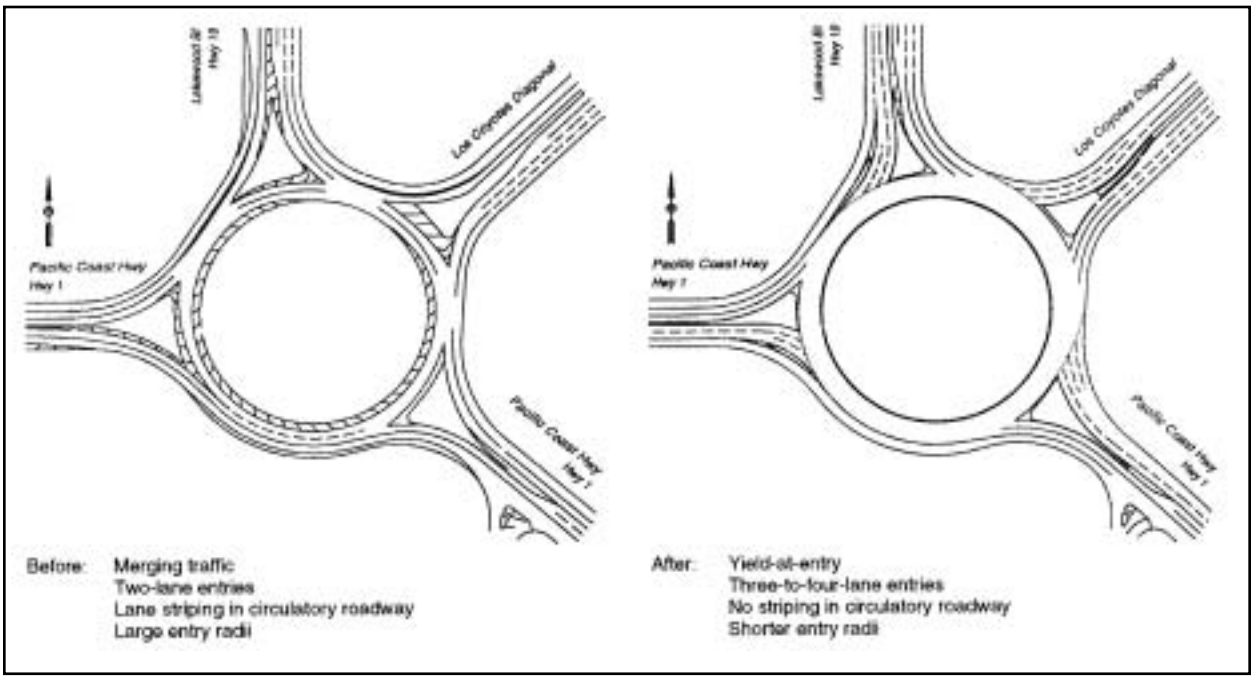

Figure 8–26: Conversion of Los Alomitos Circle (Long Beach, CA): Old Circle on Left, Roundabout on Right
Source: Leif Ourston

Figure 8–27: Conversion of Kingston, New York Traffic Circle
Source: NYSDOT