CHAPTER 2

Human Factors

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LIST OF EXHIBITS

2.0 HUMAN FACTORS

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

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

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

2.1 OVERVIEW OF HUMAN FACTORS

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

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

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

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

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

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

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

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

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

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

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

2.1.1 Positive Guidance

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

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

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

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

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

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

2.1.2 Roadway Safety Fundamentals

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

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

In the Institute for Transportation Engineers (ITE) *Traffic Safety Toolbox: A Primer on Traffic Safety,* Hauer refers to *nominal* safety as compliance with standards, warrants, guidelines and sanctioned design procedures, and *substantive* safety as the expected crash frequency and severity for a highway or roadway.[10] More recently, AASHTO published the Highway Safety Manual (HSM). The HSM provides tools to practitioners to conduct quantitative safety, allowing for safety to be quantitatively evaluated alongside other transportation performance measures such as traffic operations, environmental impacts, and construction costs in project planning and development decision-making.[11]

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

2.2 INTERSECTION USERS

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

2.2.1 Human Factors Common to All Road Users

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

Human Vision

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

Exhibit 2-1. Signs confused with background information.

Exhibit 2-2. Example of sign clutter.

Information Processing and Memory

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

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

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

User Error

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

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

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

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

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

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

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

Age

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

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

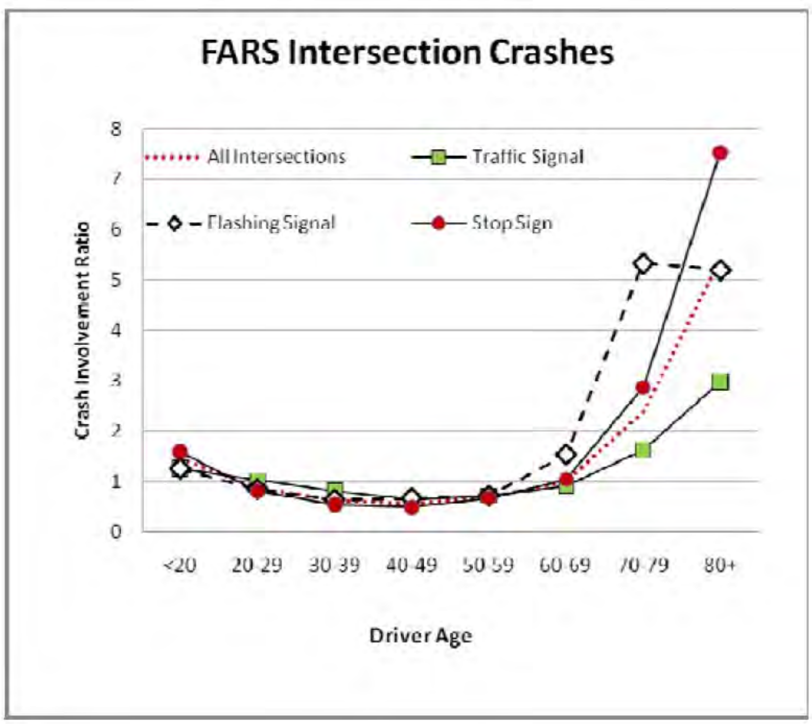

Exhibit 2-3. Fatal two-vehicle intersection crashes by traffic control device and driver age
Source: NHTSA, *Intersection Crashes among Drivers in Their 60s. 70s. and 80s.* 2011.

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

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

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

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

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

2.2.2 Motorists

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

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

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

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

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

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

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

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

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

Source: Bureau of Transportation Statistics, 2010.[17]

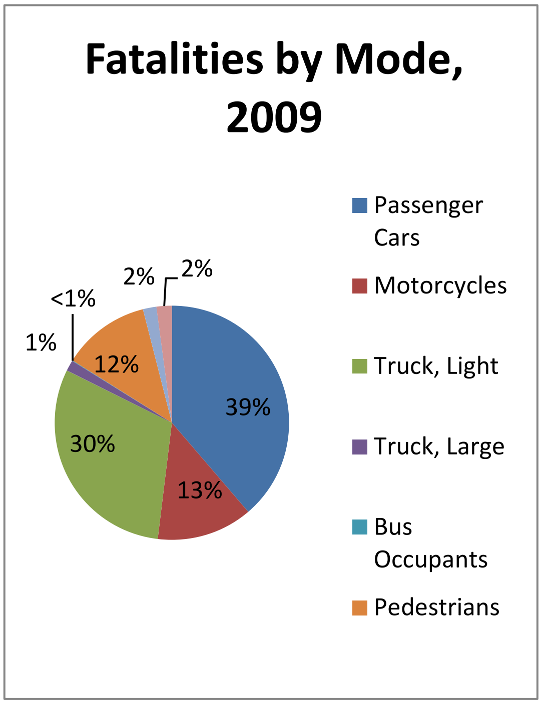

Exhibit 2-5. Fatalities by mode, 2009.
Source: Bureau of Transportation Statistics, 2009.

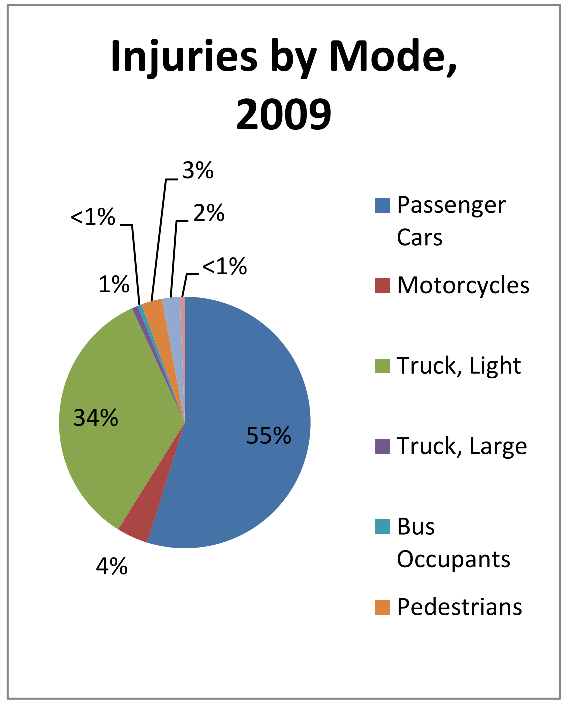

Exhibit 2-6. Injuries by mode, 2009.
Source: Bureau of Transportation Statistics, 2009.

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

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

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

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

The engineering improvements may include:

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

Red Light Running

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

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

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

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

Source: Brian Chandler

Driver Distraction

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

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

2.2.3 Bicyclists

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

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

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

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

Bicycle Users

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

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

Bicyclist Dimensions

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

Bicycle User Needs

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

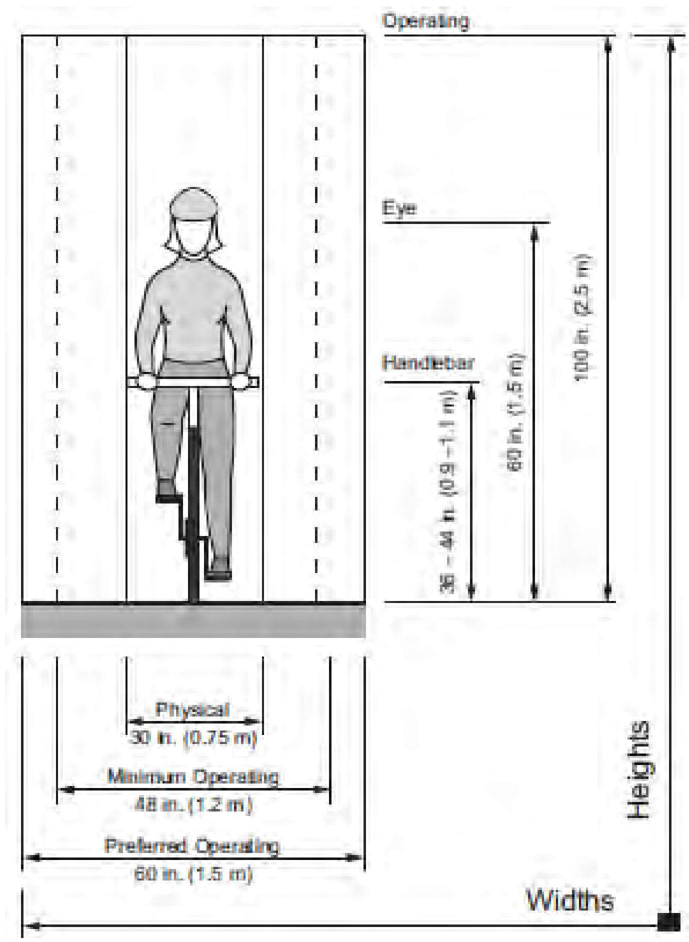

Exhibit 2-9. Typical dimensions of a bicyclist.
Source: AASHTO, *Guide for the Development of Bicycle Facilities, 4th Edition*, 2012.

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

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

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

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

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

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

Bicycle Safety

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

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

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

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

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

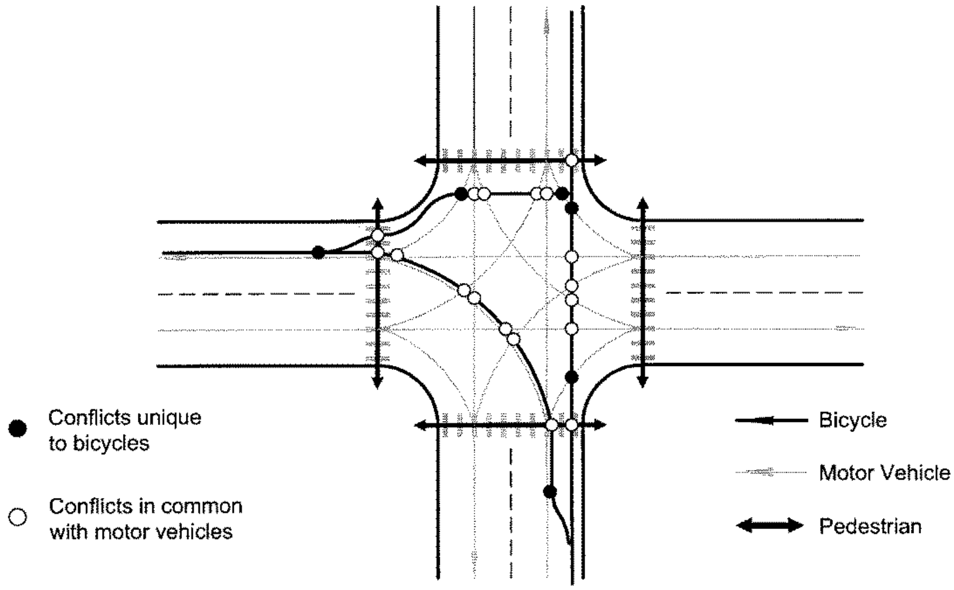

Exhibit 2-10. Bicyclist conflicts at signalized intersections.

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

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

2.2.4 Pedestrians

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

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

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

Pedestrian Dimensions

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

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

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

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

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

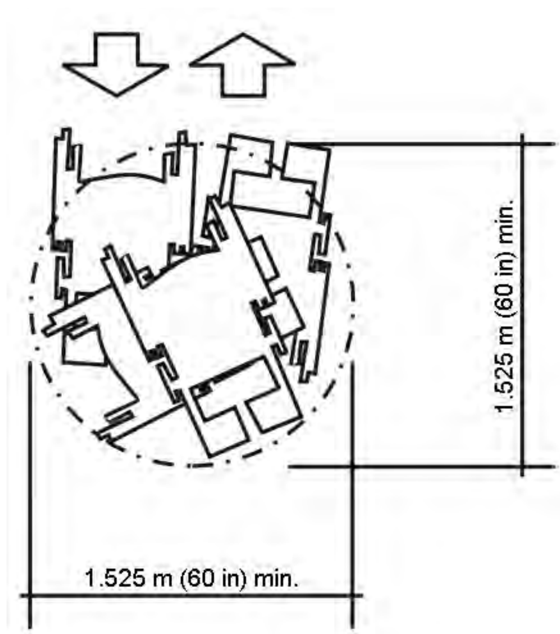

Exhibit 2-13. Typical dimensions for a turning wheelchair.

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

Pedestrian Characteristics

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

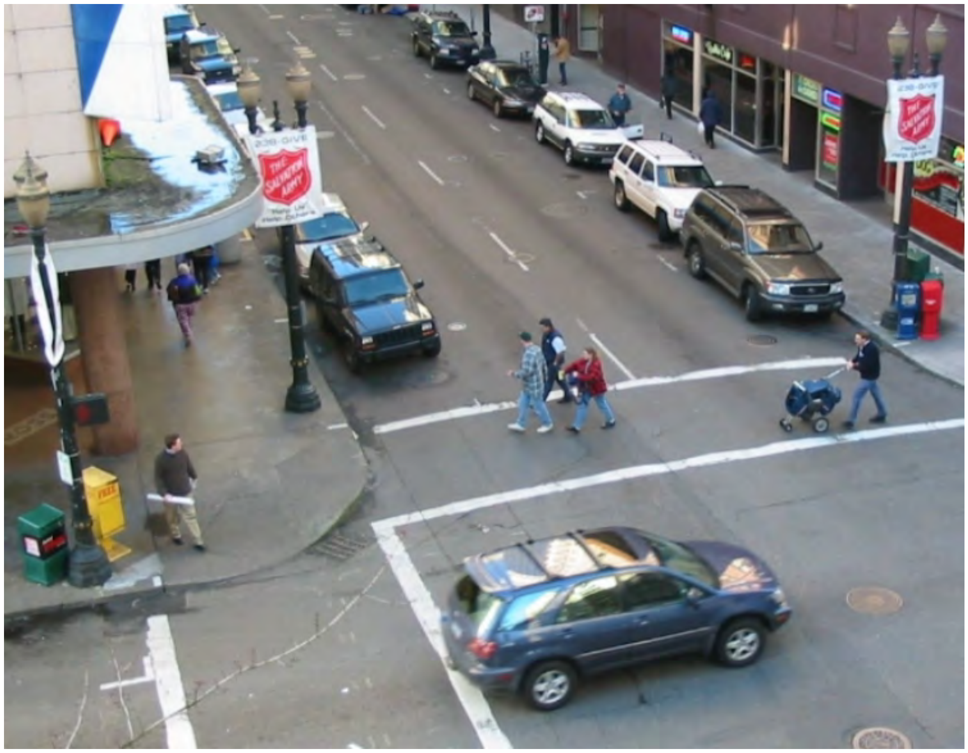

Exhibit 2-14. Crosswalks are used by a variety of users with different speed characteristics.

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

Pedestrian Conflicts

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

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

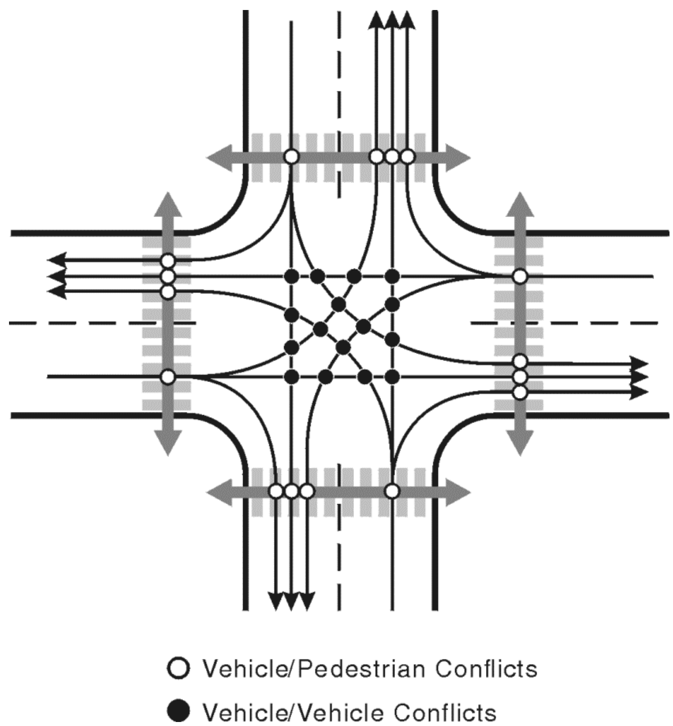

Exhibit 2-15. Pedestrian conflicts at signalized intersections.

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

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

Pedestrian Safety

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

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

From the driver's perspective, the mind goes through five psychological steps to "see" an object such as a pedestrian: selection, detection, recognition, location, and prediction. The speed of the vehicle and the experience of the driver play critical roles in the driver's ability to detect pedestrians and react appropriately. Research shows that difficulties in information processing and driver perception contribute to approximately 40 percent of all traffic crashes involving human error.[40]

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

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

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

2.3 APPLYING HUMAN FACTORS

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

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

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

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