Chapter 2—Human Factors

The purpose of this chapter is to introduce the core elements of human factors that affect the interaction of drivers and roadways. Understanding how drivers interact with the roadway allows highway agencies to plan and construct highways in a manner that minimizes human error and its resultant crashes.

This chapter is intended to support the application of knowledge presented in Parts B, C, and D; however, this chapter does not contain specific design guidance, as that is not the purpose of the *Highway Safety Manual* (HSM). For more detailed discussion of human factors and roadway elements, the reader is referred to *NCHRP Report 600: Human Factors Guidelines for Road Systems* (6).

2.1. INTRODUCTION—THE ROLE OF HUMAN FACTORS IN ROAD SAFETY

The interdisciplinary study of human factors applies knowledge from the human sciences such as psychology, physiology, and kinesiology to the design of systems, tasks, and environments for effective and safe use. The goal of understanding the effects of human factors is to reduce the probability and consequences of human error, especially the injuries and fatalities resulting from these errors, by designing systems with respect to human characteristics and limitations.

Drivers make frequent mistakes because of human physical, perceptual, and cognitive limitations. These errors may not result in crashes because drivers compensate for other drivers' errors or because the circumstances are forgiving (e.g., there is room to maneuver and avoid a crash). Near misses, or conflicts, are vastly more frequent than crashes. One study found a conflict-to-crash ratio of about 2,000 to 1 at urban intersections (28).

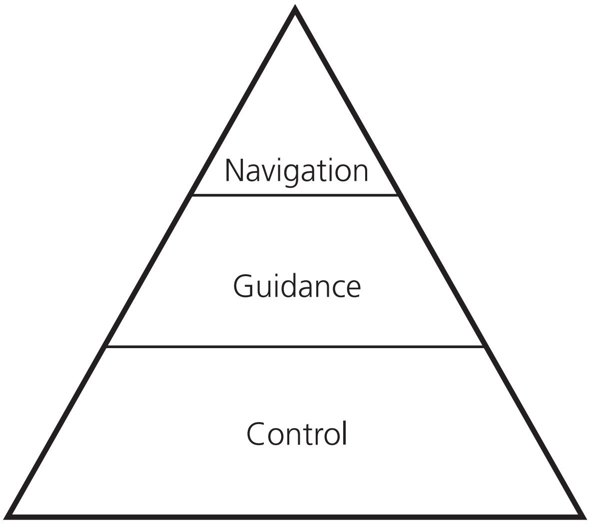
In transportation, driver error is a significant contributing factor in most crashes (41). For example, drivers can make errors of judgment concerning closing speed, gap acceptance, curve negotiation, and appropriate speeds to approach intersections. In-vehicle and roadway distractions, driver inattentiveness, and driver weariness can lead to errors. A driver can also be overloaded by the information processing required to carry out multiple tasks simultaneously, which may lead to error. To reduce their information load, drivers rely on a priori knowledge, based on learned patterns of response; therefore, they are more likely to make mistakes when their expectations are not met. In addition to unintentional errors, drivers sometimes deliberately violate traffic control devices and laws.

2.2. DRIVING TASK MODEL

Driving comprises many sub-tasks, some of which must be performed simultaneously. The three major sub-tasks are:

- *Control*—Keeping the vehicle at a desired speed and heading within the lane;
- *Guidance*—Interacting with other vehicles (following, passing, merging, etc.) by maintaining a safe following distance and by following markings, traffic control signs, and signals; and,
- *Navigation*—Following a path from origin to destination by reading guide signs and using landmarks (23).

Each of these major sub-tasks involves observing different information sources and various levels of decision making. The relationship between the sub-tasks can be illustrated in a hierarchical form, as shown in Figure 2-1. The hierarchical relationship is based on the complexity and primacy of each subtask to the overall driving task. The navigation task is the most complex of the subtasks, while the control sub-task forms the basis for conducting the other driving tasks.



Adapted from Alexander and Lunenfeld (1).

Figure 2-1. Driving Task Hierarchy

A successful driving experience requires smooth integration of the three tasks, with driver attention being switched from one to another task as appropriate for the circumstances. This can be achieved when high workload in the sub-tasks of control, guidance, and navigation does not happen simultaneously.

2.3. DRIVER CHARACTERISTICS AND LIMITATIONS

This section outlines basic driver capabilities and limitations in performing the driving tasks which can influence safety. Topics include driver attention and information processing ability, vision capability, perception-response time, and speed choice.

2.3.1. Attention and Information Processing

Driver attention and ability to process information is limited. These limitations can create difficulties because driving requires the division of attention between control tasks, guidance tasks, and navigational tasks. While attention can be switched rapidly from one information source to another, drivers only attend well to one source at a time. For example, drivers can only extract a small proportion of the available information from the road scene. It has been estimated that more than one billion units of information, each equivalent to the answer to a single yes or no question, are directed at the sensory system in one second (25). On average, humans are expected to consciously recognize only 16 units of information in one second.

To account for limited information-processing capacity while driving, drivers subconsciously determine acceptable information loads they can manage. When drivers' acceptable incoming information load is exceeded, they tend to neglect other information based on level of importance. As with decision making of any sort, error is possible during this process. A driver may neglect a piece of information that turns out to be critical, while another less-important piece of information was retained.

Scenarios illustrating circumstances in which drivers might be overloaded with information are described in Table 2-1. Each may increase the probability of driver error given human information processing limitations.

Table 2-1. Example Scenarios of Driver Overload

Scenario	Example
High demands from more than one information source	Merging into a high-volume, high-speed freeway traffic stream from a high-speed interchange ramp
The need to make a complex decision quickly	Stop or go on a yellow signal close to the stop line
The need to take large quantities of information at one time	An overhead sign with multiple panels, while driving in an unfamiliar place

As shown in Table 2-1, traffic conditions and operational situations can overload the user in many ways. Roadway design considerations for reducing driver workload include the following:

- Presenting information in a consistent manner to maintain appropriate workload;
- Presenting information sequentially, rather than all at once, for each of the control, guidance, and navigation tasks; and
- Providing clues to help drivers prioritize the most important information to assist them in reducing their workload by shedding extraneous tasks.

In addition to information processing limitations, drivers' attention is not fully within their conscious control. For drivers with some degree of experience, driving is a highly automated task. That is, driving can be, and often is, performed while the driver is engaged in thinking about other matters. Most drivers, especially on a familiar route, have experienced the phenomenon of becoming aware that they have not been paying attention during the last few miles of driving. The less demanding the driving task, the more likely it is that the driver's attention will wander, either through internal preoccupation or through engaging in non-driving tasks. Factors such as increased traffic congestion and increased societal pressure to be productive could also contribute to distracted drivers and inattention. Inattention may result in inadvertent movements out of the lane, or failure to detect a stop sign, a traffic signal, or a vehicle or pedestrian on a conflicting path at an intersection.

Driver Expectation

One way to accommodate for human information processing limitations is to design roadway environments in accordance with driver expectations. When drivers can rely on past experience to assist with control, guidance, or navigation tasks there is less to process because they only need to process new information. Drivers develop both long- and short-term expectancies. Examples of long-term expectancies that an unfamiliar driver will bring to a new section of roadway include:

- Upcoming freeway exits will be on the right-hand side of the road;
- When a minor and a major road cross, the stop control will be on the road that appears to be the minor road;
- When approaching an intersection, drivers must be in the left lane to make a left turn at the cross street; and
- A continuous through lane (on a freeway or arterial) will not end at an interchange or intersection junction.

Examples of short-term expectancies include:

- After driving a few miles on a gently winding roadway, upcoming curves will continue to be gentle;
- After traveling at a relatively high speed for some considerable distance, drivers expect the road ahead will be designed to accommodate the same speed; and
- After driving at a consistent speed on well-timed, coordinated signalized arterial corridors, drivers may not anticipate a location that operates at a different cycle length.

2.3.2. Vision

Approximately 90 percent of the information that drivers use is visual (17). While visual acuity is the most familiar aspect of vision related to driving, numerous other aspects are equally important. The following aspects of driver vision are described in this section:

- *Visual Acuity*—The ability to see details at a distance;
- *Contrast Sensitivity*—The ability to detect slight differences in luminance (brightness of light) between an object and its background;
- *Peripheral Vision*—The ability to detect objects that are outside of the area of most accurate vision within the eye;
- *Movement in Depth*—The ability to estimate the speed of another vehicle by the rate of change of visual angle of the vehicle created at the eye; and
- *Visual Search*—The ability to search the rapidly changing road scene to collect road information.

Visual Acuity

Visual acuity determines how well drivers can see details at a distance and is important for guidance and navigation tasks that require reading signs and identifying potential objects ahead.

Under ideal conditions, in daylight, with high contrast text (black on white), and unlimited time, a person with a visual acuity of 20/20, considered "normal vision," can read letters that subtend an angle of 5 minutes of arc. A person with 20/40 vision needs letters that subtend twice this angle, or 10 minutes of arc. This means that with respect to traffic signs, a person with 20/20 vision can barely read letters that are 1 inch tall at a distance of 57 feet from the sign, and letters that are 2 inches tall at a distance of 114 feet from the sign, and so on. A person with 20/40 vision would need letters of twice this height to read them at the same distances. Given that actual driving conditions often vary from the ideal conditions listed above and driver vision varies with age, driver acuity is often assumed to be less than 57 feet per inch of letter height for fonts used on highway guide signs (24).

Contrast Sensitivity

Contrast sensitivity is often recognized as having a greater impact on crash occurrence than visual acuity. Contrast sensitivity is the ability to detect small differences in luminance (brightness of light) between an object and the background. The lower the luminance of the targeted object, the more contrast is required to see the object. The target object could be a curb, debris on the road, or a pedestrian.

Good visual acuity does not necessarily imply good contrast sensitivity. For people with standard visual acuity of 20/20, the distance at which non-reflective objects are detected at night can vary by a factor of 5 to 1 (31). Drivers with normal vision but poor contrast sensitivity may have to get very close to a low-contrast target before detecting it. Experimental studies show that even alerted subjects can come as close as 30 feet before detecting a pedestrian in dark clothing standing on the left side of the road (24). In general, pedestrians tend to overestimate their own visibility to drivers at night. On average, drivers see pedestrians at half the distance at which pedestrians think they can be seen (3). This may result in pedestrians stepping out to cross a street while assuming that drivers have seen them, surprising drivers, and leading to a crash or near-miss event.

Peripheral Vision

The visual field of human eyes is large: approximately 55 degrees above the horizontal, 70 degrees below the horizontal, 90 degrees to the left, and 90 degrees to the right. However, only a small area of the visual field allows accurate vision. This area of accurate vision includes a cone of about two to four degrees from the focal point (see Figure 2-2). The lower-resolution visual field outside the area of accurate vision is referred to as peripheral vision. Although acuity is reduced, targets of interest can be detected in the low-resolution peripheral vision. Once detected, the eyes shift so that the target is seen using the area of the eye with the most accurate vision.

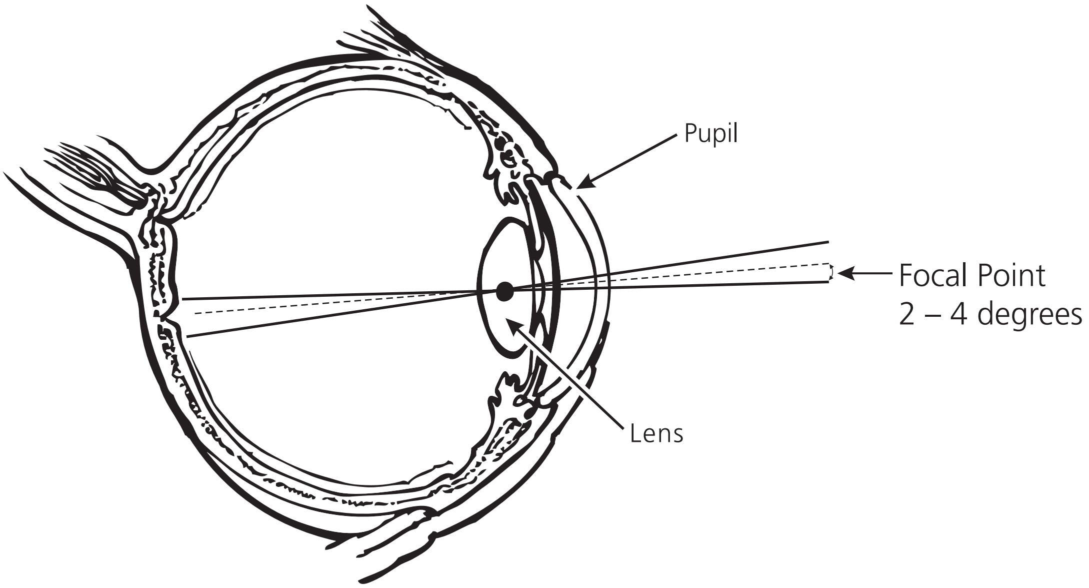


Figure 2-2. Area of Accurate Vision in the Eye

Targets that drivers need to detect in their peripheral vision include vehicles on an intersecting path, pedestrians, signs, and signals. In general, targets best detected by peripheral vision are objects that are closest to the focal point; that differ greatly from their backgrounds in terms of brightness, color, and texture; that are large; and that are moving. Studies show the majority of targets are noticed when located less than 10 to 15 degrees from the focal point and that even when targets are conspicuous, glances at angles over 30 degrees are rare (8,39).

Target detection in peripheral vision is also dependent on demands placed on the driver. The more demanding the task, the narrower the "visual cone of awareness" or the "useful field of view," and the less likely the driver is to detect peripheral targets.

Figure 2-3 summarizes the driver's view and awareness of information as the field of view increases from the focal point. Targets are seen in high resolution within the central 2–4 degrees of the field of view. While carrying out the driving task, the driver is aware of information seen peripherally, within the central 20 to 30 degrees. The driver can physically see information over a 180-degree area, but is not aware of it while driving unless motivated to direct his or her attention there.

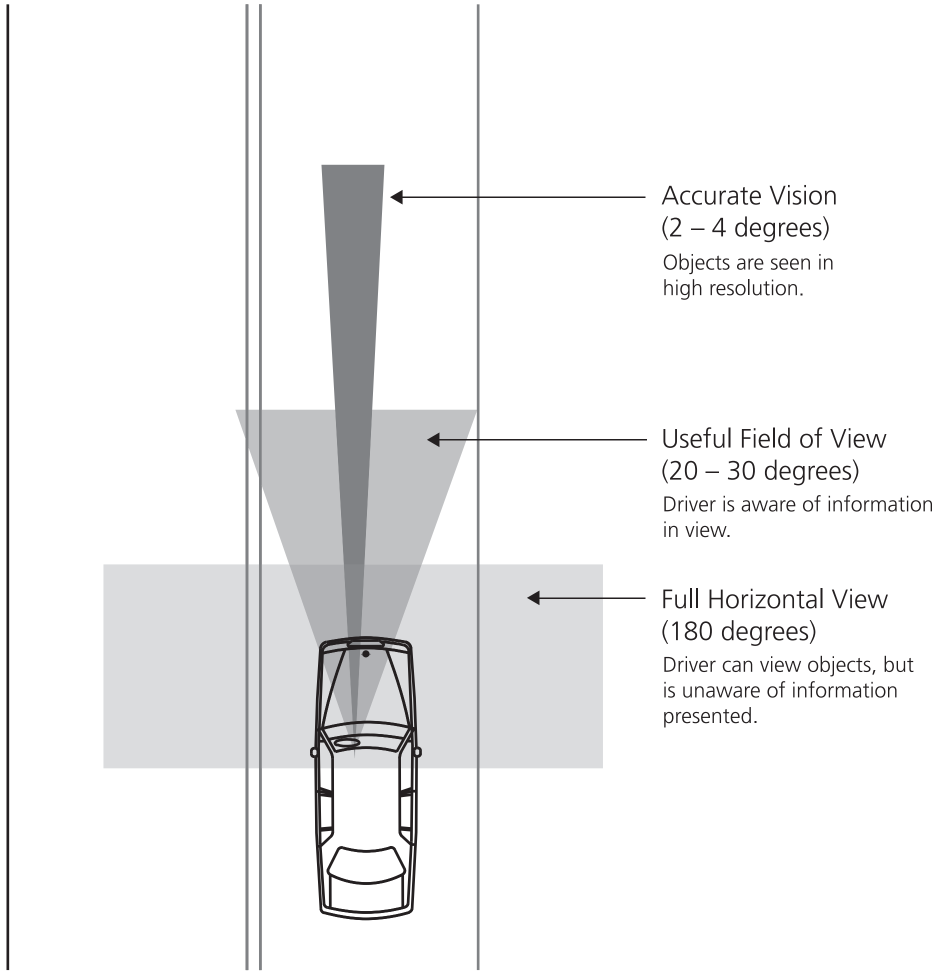
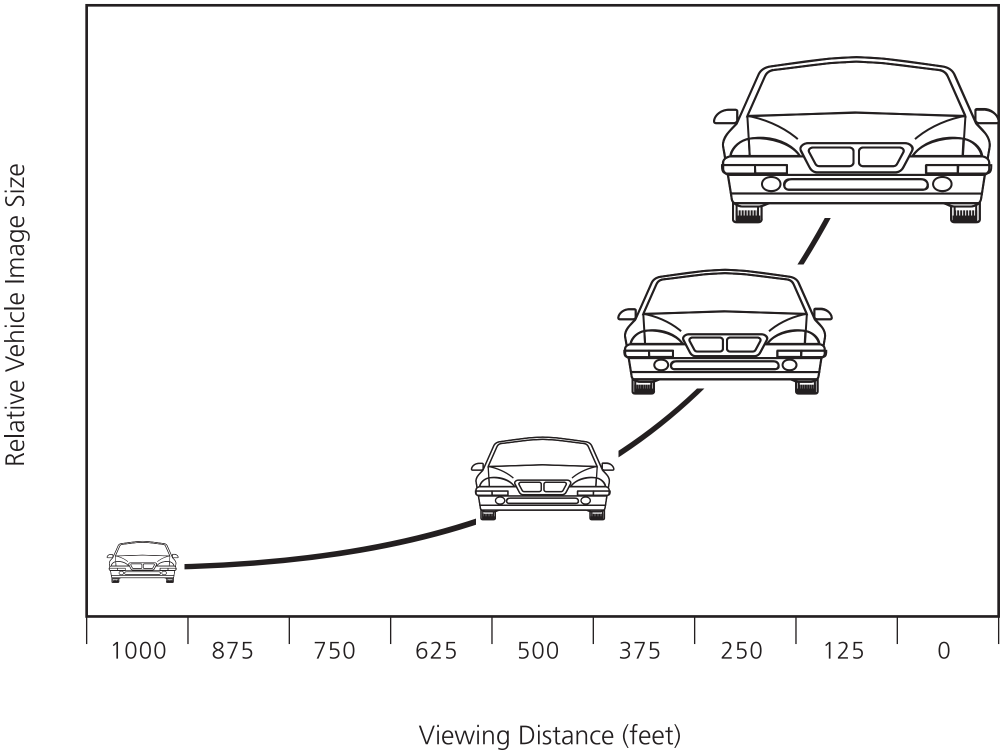


Figure 2-3. Relative Visibility of Target Object as Viewed with Peripheral Vision

Movement in Depth

Numerous driving situations require drivers to estimate movement of vehicles based on the rate of change of visual angle created at the eye by the vehicle. These situations include safe following of a vehicle in traffic, selecting a safe gap on a two-way stop-controlled approach, and passing another vehicle with oncoming traffic and no passing lane.

The primary cue that drivers use to determine their closing speed to another vehicle is the rate of change of the image size. Figure 2-4 illustrates the relative change of the size of an image at different distances from a viewer.



Adapted from Olson and Farber (14).

Figure 2-4. Relationship between Viewing Distance and Image Size

As shown in Figure 2-4, the relationship between viewing distance and image size is not a linear relationship. The fact that it is a non-linear relationship is likely the source of the difficulty drivers have in making accurate estimates of closing speed.

Drivers use the observed change in the size of a distant vehicle, measured by the rate of change of the visual angle occupied by the vehicle, to estimate the vehicle's travel speed. Drivers have difficulty detecting changes in vehicle speed over a long distance due to the relatively small amount of change in the size of the vehicle that occurs per second. This is particularly important in overtaking situations on two-lane roadways where drivers must be sensitive to the speed of oncoming vehicles. When the oncoming vehicle is at a distance at which a driver might pull out to overtake the vehicle in front, the size of that oncoming vehicle is changing gradually and the driver may not be able to distinguish whether the oncoming vehicle is traveling at a speed above or below that of average vehicles. In overtaking situations such as this, drivers have been shown to accept insufficient time gaps when passing in the face of high-speed vehicles, and to reject sufficient time gaps when passing in the face of other low-speed vehicles (5,13).

Limitations in driver perception of closing speed may also lead to increased potential for rear-end crashes when drivers traveling at highway speeds approach stopped or slowing vehicles and misjudge the stopping distance available. This safety concern is compounded when drivers are not expecting this situation. One example is on a rural two-lane roadway where a left-turning driver must stop in the through lane to wait for an acceptable gap in opposing traffic. An approaching driver may not detect the stopped vehicle. In this circumstance, the use of turn signals or visibility of brake lights may prove to be a crucial cue for determining that the vehicle is stopped and waiting to turn.

Visual Search

The driving task requires active search of the rapidly changing road scene, which requires rapid collection and absorption of road information. While the length of an eye fixation on a particular subject can be as short as $^{1}/_{10}$ of a second for a simple task such as checking lane position, fixation on a complex subject can take up to 2 seconds (35). By understanding where drivers fix their eyes while performing a particular driving task, information can be placed in the most effective location and format.

Studies using specialized cameras that record driver-eye movements have revealed how drivers distribute their attention amongst the various driving sub-tasks, and the very brief periods of time (fixations) drivers can allocate to any one target while moving. According to the study, drivers on an open road fixated approximately 90 percent of the time within a 4-degree region vertically and horizontally from a point directly ahead of the driver (26). Within this focused region, slightly more than 50 percent of all eye fixations occurred to the right side of the road where traffic signs are found. This indicates that driver visual search is fairly concentrated.

The visual search pattern changes when a driver is negotiating a horizontal curve as opposed to driving on a tangent. On tangent sections, drivers can gather both path and lateral position information by looking ahead. During curve negotiation, visual demand is essentially doubled, as the location of street sign and roadside information is displaced (to the left or to the right) from information about lane position. Eye movement studies show that drivers change their search behavior several seconds prior to the start of the curve. These findings suggest that advisory curve signs placed just prior to the beginning of the approach zone may reduce visual search challenges (38).

Other road users, such as pedestrians and cyclists, also have a visual search task. Pedestrians can be observed to conduct a visual search if within three seconds of entering the vehicle path the head is turned toward the direction in which the vehicle would be coming from. The visual search varies with respect to the three types of threats: vehicles from behind, from the side, and ahead. Vehicles coming from behind require the greatest head movement and are searched for the least. These searches are conducted by only about 30 percent of pedestrians. Searches for vehicles coming from the side and from ahead are more frequent, and are conducted by approximately 50 and 60 percent of pedestrians, respectively. Interestingly between 8 and 25 percent of pedestrians at signalized downtown intersections without auditory signals do not look for threats (42).

2.3.3. Perception-Reaction Time

Perception-reaction time (PRT) includes time to detect a target, process the information, decide on a response, and initiate a reaction. Although higher values such as 1.5 or 2.5 seconds are commonly used because it accommodates the vast percentage of drivers in most situations, it is important to note that PRT is not fixed. PRT depends on human elements discussed in previous sections, including information processing, driver alertness, driver expectations, and vision.

The following sections describe the components of perception-reaction time: detection, decision, and response.

Detection

The initiation of PRT begins with detection of an object or obstacle that may have potential to cause a crash. At this stage the driver does not know whether the observed object is truly something to be concerned with, and if so, the level of concern.

Detection can take a fraction of a second for an expected object or a highly conspicuous object placed where the driver is looking. However, at night an object that is located several degrees from the line of sight and is of low contrast compared to the background may not be seen for many seconds. The object cannot be seen until the contrast of the object exceeds the threshold contrast sensitivity of the driver viewing it.

Failures in detection are most likely for objects that are:

- More than a few degrees from the driver's line of sight;
- Minimally contrasted with the background;

- Small in size;
- Seen in the presence of glare;
- Not moving; and
- Unexpected and not being actively searched for by the driver.

Once an object or obstacle has been detected, the details of the object or obstacle must be determined in order to have enough information to make a decision. As discussed in the next section, identification will be delayed when the object being detected is unfamiliar and unexpected. For example, a low-bed, disabled tractor-trailer with inadequate reflectors blocking a highway at night will be unexpected and hard to identify.

Decision

Once an object or obstacle has been detected and enough information has been collected to identify it, a decision can be made as to what action to take. The decision does not involve any action, but rather is a mental process that takes what is known about the situation and determines how the driver will respond.

Decision time is highly dependent on circumstances that increase the complexity of a decision or require that it be made immediately. Many decisions are made quickly when the response is obvious. For example, when the driver is a substantial distance from the intersection and the traffic light turns red, minimal time is needed to make the decision. If, on the other hand, the driver is close to the intersection and the traffic light turns yellow, there is a dilemma: is it possible to stop comfortably without risking being rear-ended by a following vehicle, or is it better to proceed through the intersection? The time to make this stop-or-go decision will be longer given that there are two reasonable options and more information to process.

Decision making also takes more time when there is an inadequate amount of information or an excess amount. If the driver needs more information, they must search for it. On the other hand, if there is too much information, the driver must sort through it to find the essential elements, which may result in unnecessary effort and time. Decision making also takes more time when drivers have to determine the nature of unclear information, such as bits of reflection on a road at night. The bits of reflection may result from various sources, such as harmless debris or a stopped vehicle.

Response

When the information has been collected and processed and a decision has been made, time is needed to respond physically. Response time is primarily a function of physical ability to act upon the decision and can vary with age, lifestyle (athletic, active, or sedentary), and alertness.

Perception-Reaction Times in Various Conditions

Various factors present in each unique driving situation affect driver perception-reaction time; therefore, it is not a fixed value. Guidance for a straightforward detection situation comes from a study of “stopping-sight distance” perception-reaction times. The experiment was conducted in daylight while a driver was cresting a hill and looking at the road at the very moment an object partially blocking the road came into view without warning. The majority of drivers (85 percent) reacted within 1.3 seconds, and 95 percent of drivers reacted within 1.6 seconds (30). In a more recent study which also examined drivers’ response to unexpected objects entering the roadway, it was concluded that a perception-reaction time of approximately 2.0 sec seems to be inclusive of nearly all the subjects’ responses under all conditions tested (12).

However, the 2.0 -second perception-reaction time may not be appropriate for application to a low contrast object seen at night. Although an object can be within the driver’s line of sight for hundreds of feet, there may be insufficient light from low beam headlights and insufficient contrast between the object and the background for a driver to see it. Perception-reaction time cannot be considered to start until the object has reached the level of visibility necessary for detection, which varies from driver to driver and is influenced by the driver’s state of expectation. A driving simulator study found that drivers who were anticipating having to respond to pedestrian targets on the road edge took an average of 1.4 seconds to respond to a high-contrast pedestrian, and 2.8 seconds to respond to a low-contrast pedestrian, indicating a substantial impact of contrast on perception-reaction time (34). Glare lengthened these perception-reaction times even further. It should be noted that subjects in experiments are abnormally alert, and real-world reaction times could be expected to be longer.

As is clear from this discussion, perception-reaction time is not a fixed value. It is dependent on driver vision, conspicuity of a traffic control device or objects ahead, the complexity of the response required, and the urgency of that response.

2.3.4. Speed Choice

A central aspect of traffic safety is driver speed choice. While speed limits influence driver speed choice, these are not the only or the most important influences. Drivers select speed using perceptual and “road message” cues. Understanding these cues can help establish self-regulating speeds with minimal or no enforcement.

This section includes a summary of how perceptual and road message cues influence speed choice.

Perceptual Cues

A driver’s main cue for speed choice comes from peripheral vision. In experiments where drivers are asked to estimate their travel speed with their peripheral vision blocked (only the central field of view can be used), the ability to estimate speed is poor. This is because the view changes very slowly in the center of a road scene. If, on the other hand, the central portion of the road scene is blocked out, and drivers are asked to estimate speed based on the peripheral view, drivers do much better (36).

Streaming (or “optical flow”) of information in peripheral vision is one of the greatest influences on drivers’ estimates of speed. Consequently, if peripheral stimuli are close by, then drivers will feel they are going faster than if they encounter a wide-open situation. In one study, drivers were asked to drive at 60 mph with the speedometer covered. In an open-road situation, the average speed was 57 mph. After the same instructions, but along a tree-lined route, the average speed was 53 mph (38). The researchers believe that the trees near the road provided peripheral stimulation, giving a sense of higher speed.

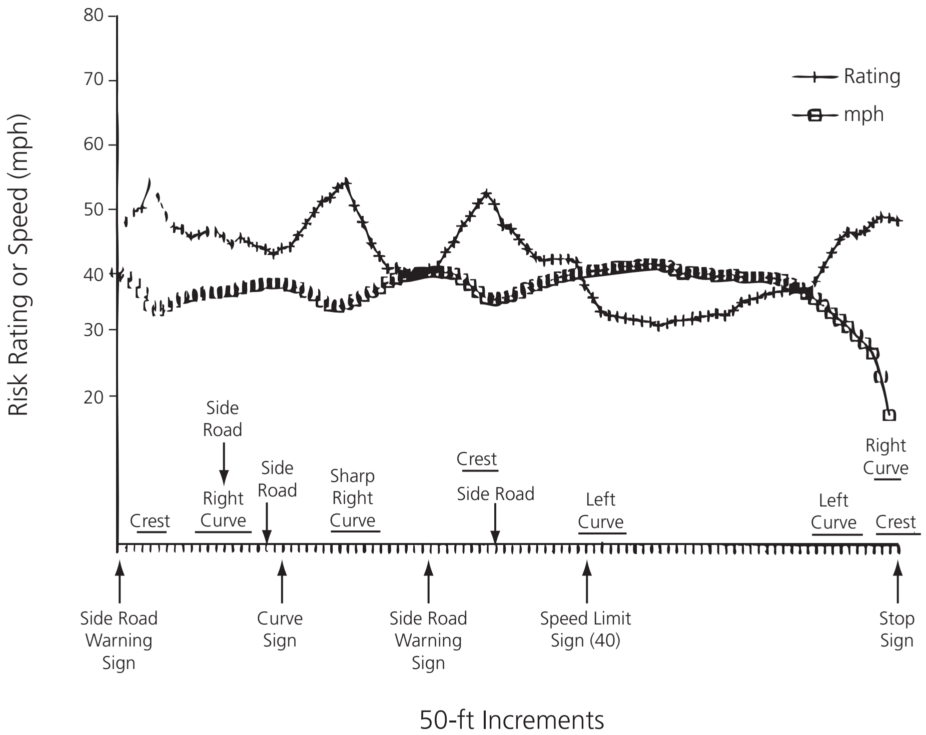
Noise level is also an important cue for speed choice. Several studies examined how removing noise cues influenced travel speed. While drivers’ ears were covered (with ear muffs), they were asked to travel at a particular speed. All drivers underestimated how fast they were going and drove 4 to 6 mph faster than when the usual sound cues were present (10, 11). With respect to lowering speeds, it has been counter-productive to progressively quiet the ride in cars and to provide smoother pavements.

Another aspect of speed choice is speed adaptation. This is the experience of leaving a freeway after a long period of driving and having difficulty conforming to the speed limit on an arterial road. One study required subjects to drive for 20 miles on a freeway and then drop their speeds to 40 mph on an arterial road. The average speed on the arterial was 50 miles per hour (37). This speed was higher than the requested speed despite the fact that these drivers were perfectly aware of the adaptation effect, told the researchers they knew this effect was happening, and tried to bring their speed down. The adaptation effect was shown to last up to five or six minutes after leaving a freeway, and to occur even after very short periods of high speed (37). Various access management techniques, sign placement, and traffic calming devices may help to reduce speed adaptation effects.

Road Message Cues

Drivers may interpret the roadway environment as a whole to encourage fast or slow speeds depending on the effects of the geometry, terrain, or other roadway elements. Even though drivers may not have all the information for correctly assessing a safe speed, they respond to what they can see. Drivers tend to drive faster on a straight road with several lanes, wide shoulders, and a wide clear zone, than drivers on a narrow, winding road with no shoulders or a cliff on the side. For example, speeds on rural highway tangents are related to cross-section and other variables, such as the radius of the curve before and after the tangent, available sight distance, and general terrain (33).

The difficulty of the driving task due to road geometry (e.g., sharp curves, narrow shoulders) strongly influences driver perception of risk and, in turn, driver speed. Figure 2-5 shows the relationship between risk perception, speed, various geometric elements, and control devices. These relationships were obtained from a study in which drivers travelled a section of roadway twice. Each time the speed of the vehicle was recorded. The first time test subjects travelled the roadway, they drove the vehicle. The second time the test subjects travelled the roadway, there were passengers in the vehicle making continuous estimates of the risk of a crash (33). As shown in Figure 2-5, where drivers perceived the crash risk to be greater (e.g., sharp curves, limited sight distance), they reduced their travel speed.



Source: Horizontal Alignment Design Consistency for Rural Two-lane Highways, RD-94-034, FHWA.

Figure 2-5. Perceived Risk of a Crash and Speed

Speed advisory plaques on curve warning signs appear to have little effect on curve approach speed, probably because drivers feel they have enough information from the roadway itself and select speed according to the appearance of the curve and its geometry. One study recorded the speeds of 40 drivers unfamiliar with the route and driving on curves with and without speed plaques. Although driver eye movements were recorded and drivers were found to look at the warning sign, the presence of a speed plaque had no effect on drivers' selected speed (22).

In contrast, a study of 36 arterial tangent sections found some influence of speed limit, but no influence of road design variables on drivers' speed. The sections studied had speed limits that ranged from 25 to 55 mph. Speed limit accounted for 53 percent of the variance in speed, but factors such as alignment, cross-section, median presence, and roadside variables were not found to have a statistically significantly effect on operating speed (21).

2.4. POSITIVE GUIDANCE

Knowledge of human limitations in information processing and human reliance on expectation to compensate for those limitations in information processing, led to the "positive guidance" approach to highway design. This approach is based on a combination of human factors and traffic engineering principles (18). The central principle is that road design that corresponds with driver limitations and expectations increases the likelihood of drivers responding to situations and information correctly and quickly. Conversely, when drivers are not provided with information in a timely fashion, when they are overloaded with information, or when their expectations are not met, slowed responses and errors may occur.

Design that conforms to long-term expectancies reduces the chance of driver error. For example, drivers expect that there are no traffic signals on freeways and that freeway exits are on the right. If design conforms to those expectancies it reduces the risk of a crash. Short-term expectancies can also be impacted by design decisions. An example of a short-term expectation is that subsequent curves on a section of road are gradual, given that all previous curves were gradual.

With respect to traffic control devices, the positive guidance approach emphasizes assisting the driver with processing information accurately and quickly by considering the following:

- *Primacy*—Determine the placements of signs according to the importance of information, and avoid presenting the driver with information when and where the information is not essential.
- *Spreading*—Where all the information required by the driver cannot be placed on one sign or on a number of signs at one location, spread the signage along the road so that information is given in small chunks to reduce information load.
- *Coding*—Where possible, organize pieces of information into larger units. Color and shape coding of traffic signs accomplishes this organization by representing specific information about the message based on the color of the sign background and the shape of the sign panel (e.g., warning signs are yellow, regulatory signs are white).
- *Redundancy*—Say the same thing in more than one way. For example, the stop sign in North America has a unique shape and message, both of which convey the message to stop. A second example of redundancy is to give the same information by using two devices (e.g., “no passing” indicated with both signs and pavement markings).

2.5. IMPACTS OF ROAD DESIGN ON THE DRIVER

This section considers major road design elements, related driver tasks, and human errors associated with common crash types. It is not intended to be a comprehensive summary, but is intended to provide examples to help identify opportunities It is not intended to be a comprehensive summary, but is intended to provide examples to help identify opportunities where an understanding of the influence of human factors can be applied to improve design.

2.5.1. Intersections and Access Points

As discussed in Section 2.2, the driving task involves control, guidance, and navigation elements. At intersections, each of these elements presents challenges:

- *Control*—The path through the intersection is typically unmarked and may involve turning;
- *Guidance*—There are numerous potential conflicts with other vehicles, pedestrians, and cyclists on conflicting paths; and
- *Navigation*—Changes in direction are usually made at intersections, and road name signing can be difficult to locate and read in time to accomplish any required lane changes.

In the process of negotiating any intersection, drivers are required to:

- Detect the intersection;
- Identify signalization and appropriate paths;
- Search for vehicles, pedestrians, and bicyclists on a conflicting path;
- Assess adequacy of gaps for turning movements;
- Rapidly make a stop/go decision on the approach to a signalized intersection when in the decision zone; and
- Successfully complete through or turning maneuvers.

Thus, intersections place high demands on drivers in terms of visual search, gap estimation, and decision-making requirements that increase the potential for error. Road crash statistics show that although intersections constitute a small portion of the highway network, about 50 percent of all urban crashes and 25 percent of rural crashes are related to intersections (43). A study of the human factors contributing causes to crashes found that the most frequent type of error was "improper lookout," and that 74 percent of these errors occurred at intersections. In about half of the cases, drivers failed to look, and in about half of the cases, drivers "looked but did not see" (15, 41).

Errors Leading to Rear-End and Sideswipe Crashes

Errors leading to rear-end and sideswipe crashes include the following:

- Assuming that the lead driver, once moving forward, will continue through the stop sign, but the lead driver stops due to late recognition that there is a vehicle or pedestrian on a conflicting path.
- Assuming that the lead driver will go through a green or yellow light, but the lead driver stops due to greater caution. Drivers following one another can make differing decisions in this "dilemma zone". As speed increases, the length of the dilemma zone increases. Additionally, as speed increases, the deceleration required is greater and the probability of a rear-end crash may also increase.
- Assuming that the lead driver will continue through a green or yellow light, but the lead driver slows or stops due to a vehicle entering or exiting an access point just prior to the intersection; or a vehicle exiting an access point suddenly intruding into the lane; or a pedestrian crossing against a red light.
- Changing lanes to avoid a slowing or stopped vehicle, with inadequate search.
- Distracting situations that may lead to failure to detect slowing or stopping vehicles ahead. Distracting situations could include:
  - Preoccupation with personal thoughts,
  - Attention directed to non-driving tasks within the vehicle,
  - Distraction from the road by an object on the roadside, or
  - Anticipation of downstream traffic signal.

Errors Leading to Turning Crashes

Turning movements are often more demanding with respect to visual search, gap judgment, and path control than are through movements. Turning movements can lead to crashes at intersections or access points due to the following:

- Perceptual limitations,
- Visual blockage,
- Permissive left-turn trap, and
- Inadequate visual search.

A description of these common errors that can lead to turning crashes at intersections follows.

Perceptual Limitations

Perceptual limitations in estimating closing vehicle speeds could lead to left-turning drivers selecting an inappropriate gap in oncoming traffic. Drivers turning left during a permissive green light may not realize that an oncoming vehicle is moving at high speed.

Visual Blockage

A visual blockage may limit visibility of an oncoming vehicle when making a turn at an intersection. About 40 percent of intersection crashes involve a view blockage (41). Windshield pillars inside the vehicle, utility poles, commercial signs, and parked vehicles may block a driver's view of a pedestrian, bicyclist, or motorcycle on a conflicting path at a critical point during the brief glance that a driver may make in that direction. Visual blockages also occur where the offset of left-turn bays results in vehicles in the opposing left-turn lane blocking a left-turning driver's view of an oncoming through vehicle.

Permissive Left-turn Trap

On a high-volume road, drivers turning left on a permissive green light may be forced to wait for a yellow light to make their turn, at which time they come into conflict with oncoming drivers who continue through a red light.

Inadequate Visual Search

Drivers turning right may concentrate their visual search only on vehicles coming from the left and fail to detect a bicyclist or pedestrian crossing from the right (1). This is especially likely if drivers do not stop before turning right on red, and as a result give themselves less time to search both to the left and right.

Errors Leading to Angle Crashes

Angle crashes can occur due to:

- Delayed detection of an intersection (sign or signal) at which a stop is required;
- Delayed detection of crossing traffic by a driver who deliberately violates the sign or signal; or
- Inadequate search for crossing traffic or appropriate gaps.

Drivers may miss seeing a signal or stop sign because of inattention, or a combination of inattention and a lack of road message elements that would lead drivers to expect the need to stop. For example, visibility of the intersection pavement or the crossing traffic may be poor, or drivers may have had the right-of-way for some distance and the upcoming intersection does not look like a major road requiring a stop. In an urban area where signals are closely spaced, drivers may inadvertently attend to the signal beyond the signal they face. Drivers approaching at high speeds may become caught in the dilemma zone and continue through a red light.

Errors Leading to Crashes with Vulnerable Road Users

Pedestrian and bicycle crashes often result from inadequate search and lack of conspicuity. The inadequate search can be on the part of the driver, pedestrian, or bicyclist. In right-turning crashes, pedestrians and drivers have been found to be equally guilty of failure to search. In left-turning crashes, drivers are more frequently found at fault, likely because the left-turn task is more visually demanding than the right-turn task for the driver (20).

Examples of errors that may lead to pedestrian crashes include:

- Pedestrians crossing at traffic signals rely on the signal giving them the right-of-way, and fail to search adequately for turning traffic (35).
- Pedestrians step into the path of a vehicle that is too close for the driver to have sufficient time to stop.

When accounting for perception-response time, a driver needs over 100 ft to stop when traveling at 30 mph. Pedestrians are at risk because of the time required for drivers to respond and because of the energy involved in collisions, even at low speeds. Relatively small changes in speed can have a large impact on the severity of a pedestrian crash. A pedestrian hit at 40 mph has an 85 percent chance of being killed; at 30 mph the risk is reduced to 45 percent; at 20 mph the risk is reduced to 5 percent (27).

Poor conspicuity, especially at night, greatly increases the risk of a pedestrian or bicyclist crash. Clothing is often dark, providing little contrast to the background. Although streetlighting helps drivers see pedestrians, streetlighting can create uneven patches of light and dark which makes pedestrians difficult to see at any distance.

2.5.2. Interchanges

At interchanges drivers can be traveling at high speeds, and at the same time can be faced with high demands in navigational, guidance, and control tasks. The number of crashes at interchanges as a result of driver error is influenced by the following elements of design:

- Entrance ramp/merge length,
- Distance between successive ramp terminals,
- Decision sight distance and guide signing, and
- Exit ramp design.

Entrance Ramp/Merge Length

If drivers entering a freeway are unable to accelerate to the speed of the traffic stream (e.g., due to acceleration lane length, the grade of the ramp, driver error, or heavy truck volumes), entering drivers will merge with the mainline at too slow a speed and may risk accepting an inadequate gap. Alternatively, if the freeway is congested or if mainline vehicles are tailgating, it may be difficult for drivers to find an appropriate gap into which to merge.

Distance Between Successive Ramp Terminals

If the next exit ramp is close to the entrance ramp, entering (accelerating) drivers will come into conflict with exiting (decelerating) drivers along the weaving section and crashes may increase (16, 40). Given the visual search required by both entering and exiting drivers, and the need to look away from the traffic immediately ahead in order to check for gaps in the adjacent lane, sideswipe and rear-end crashes can occur in weaving sections. Drivers may fail to detect slowing vehicles ahead, or vehicles changing lanes in the opposing direction, in time to avoid contact.

Decision Sight Distance and Guide Signing

Increased risk of error occurs in exit locations because drivers try to read signs, change lanes, and decelerate comfortably and safely. Drivers may try to complete all three tasks simultaneously, thereby increasing their willingness to accept smaller gaps while changing lanes or to decelerate at greater than normal rates.

Exit Ramp Design

If the exit ramp radius is small and requires the exiting vehicle to decelerate more than expected, the speed adaptation effect discussed in the previous section can lead to insufficient speed reductions. Also, a tight exit ramp radius or an unusually long vehicle queue extending from the ramp terminal can potentially surprise drivers, leading to run-off-the-road and rear-end crashes.

2.5.3. Divided, Controlled-Access Mainline

Compared to intersections and interchanges, the driving task on a divided, controlled-access mainline is relatively undemanding with respect to control, guidance, and navigational tasks. This assumes that the mainline has paved shoulders, wide clear zones, and is outside the influence area of interchanges.

A description of each of these common errors and other factors that lead to crashes on divided, controlled-access mainline roadway sections is provided below.

Driver Inattention and Sleepiness

Low mental demand can lead to driver inattention and sleepiness, resulting in inadvertent (drift-over) lane departures. Sleepiness is strongly associated with time of day. It is particularly difficult for drivers to resist falling asleep in the early-morning hours (2 to 6 a.m.) and in the mid-afternoon. Sleepiness arises from the common practices of reduced sleep and working shifts. Sleepiness also results from alcohol and other drug use (32). Shoulder-edge rumble strips are one example of a countermeasure that can be used to potentially reduce run-off-the-road crashes. They provide strong auditory and tactile feedback to drivers whose cars drift off the road because of inattention or impairment.

Slow-Moving or Stopped Vehicles Ahead

Mainline crashes can also occur when drivers encounter slow-moving or stopped vehicles which, except in congested traffic, are in a freeway through lane. Drivers' limitations in perceiving closing speed result in a short time to respond once the driver realizes the rapidity of the closure. Alternatively, drivers may be visually attending to the vehicle directly ahead of them and may not notice lane changes occurring beyond. If the lead driver is the first to encounter the stopped vehicle, realizes the situation just in time, and moves rapidly out of the lane, the stopped vehicle is uncovered at the last second, leaving the following driver with little time to respond.

Animals in the Road

Another common mainline crash type is with animals, particularly at night. Such crashes may occur because an animal enters the road immediately in front of the driver, leaving little or no time for the driver to detect or avoid it. Low conspicuity of animals is also a problem. Given the similarity in coloring and reflectance between pedestrians and animals, the same driver limitations can be expected to apply to animals as to pedestrians in dark clothing. Based on data collected for pedestrian targets, the majority of drivers traveling at speeds much greater than 30 mph and with low-beam headlights would not be able to detect an animal in time to stop (4).

2.5.4. Undivided Roadways

Undivided roadways vary greatly in design and therefore in driver workload and perceived risk. Some undivided roadways may have large-radius curves, mostly level grades, paved shoulders, and wide clear zones. On such roads, and in low levels of traffic, the driving task can be very undemanding, resulting in monotony and, in turn, possibly driver inattention and/or sleepiness. On the other hand, undivided roadways may be very challenging in design, with tight curves, steep grades, little or no shoulder, and no clear zone. In this case, the driving task is considerably more demanding.

Driver Inattention and Sleepiness

As described previously for the controlled-access mainline, inadvertent lane departures can result when drivers are inattentive, impaired by alcohol or drugs, or sleepy. On an undivided highway, these problems lead to run-off-the-road and head-on crashes. Rumble strips are effective in alerting drivers about to leave the lane, and have been shown to be effective in reducing run-off-the-road and cross-centerline crashes, respectively (7,9).

Inadvertent Movement into Oncoming Lane

The vast majority of head-on crashes occur due to inadvertent movement into the oncoming lane. Contrary to some expectations, only about 4 percent of head-on crashes are related to overtaking (15). Centerline rumble strips are very effective in reducing such crashes as they alert inattentive and sleepy drivers. Although overtaking crashes are infrequent, they have a much higher risk of injury and fatality than other crashes. As discussed previously, drivers are very limited in their ability to perceive their closing speed to oncoming traffic. They tend to select gaps based more on distance than on speed, leading to inadequate gaps when the oncoming vehicle is traveling substantially faster than the speed limit. Passing lanes and four-lane passing sections greatly alleviate driver workload and the risk of error involved in passing.

Driver Speed Choice

On roads with demanding geometry, driver speed choice when entering curves may be inappropriate, leading to run-off-the-road crashes. Treatments which improve delineation are often applied under the assumption that run-off-the-road crashes occur because the driver did not have adequate information about the direction of the road path. However, studies have not supported this assumption (29).

Slow-Moving or Stopped Vehicles Ahead

For the controlled-access mainline, rear-end and sideswipe crashes occur when drivers encounter unexpected slowing or stopped vehicles and realize too late their closing speed.

Poor Visibility of Vulnerable Road Users or Animals

Vulnerable road user and animal crashes may occur due to low contrast with the background and drivers' inability to detect pedestrians, cyclists, or animals in time to stop.

2.6. SUMMARY—HUMAN FACTORS AND THE HSM

This chapter described the key factors of human behavior and ability that influence how drivers interact with the roadway. The core elements of the driving task were outlined and related to human ability so as to identify areas where humans may not always successfully complete the tasks. There is potential to reduce driver error and associated crashes by accounting for the following driver characteristics and limitations described in the chapter:

- *Attention and information processing*—Drivers can only process a limited amount of information and often rely on past experience to manage the amount of new information they must process while driving. Drivers can process information best when it is presented in accordance with expectations, sequentially to maintain a consistent level of demand, and in a way that it helps drivers prioritize the most essential information.
- *Vision*—Approximately 90 percent of the information used by a driver is obtained visually (17). It is important that the information be presented in a way that considers the variability of driver visual capability so that users can see, comprehend, and respond to it appropriately.
- *Perception-reaction time*—The amount of time and distance needed by one driver to respond to a stimulus (e.g., hazard in road, traffic control device, or guide sign) depends on human elements, including information processing, driver alertness, driver expectations, and vision.
- *Speed choice*—Drivers use perceptual and road message cues to determine a speed they perceive to be safe. Information taken in through peripheral vision may lead drivers to speed up or slow down depending on the distance from the vehicle to the roadside objects (38). Drivers may also drive faster than they realize after adapting to highway speeds and subsequently entering a lower-level facility (37).

Knowledge of both engineering principles and the effects of human factors can be applied through the positive guidance approach to road design. The positive guidance approach is based on the central principle that road design that corresponds with driver limitations and expectations increases the likelihood of drivers responding to situations and information correctly and quickly. When drivers are not provided or do not accept information in a timely fashion, when they are overloaded with information, or when their expectations are not met, slowed responses and errors may occur.

An understanding of human factors and their affects can be applied to all projects regardless of the project focus. Parts B, C, and D provide specific guidance on the roadway safety management process, estimating safety effects of design alternatives, and predicting safety on different facilities. Considering the effect of human factors on these activities can improve decision making and design considerations in analyzing and developing safer roads.

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