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Advanced Warning Technologies: Collision, Intersection Incursion

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40.1 Introduction

Collisions between motor vehicles on roadways or at intersections are a significant issue facing the motoring public. According to the Fatality Accident Reporting System (National Highway Transportation Safety Administration, 2007), in the United States, in 2007, 37% of the approximately 41,000 fatalities were related to multiple vehicle crashes while approximately 15% of all fatalities occurred at intersections. In response to this public health issue researchers and product designers have developed and evaluated technologies that can warn drivers of imminent collisions and can manipulate vehicle control systems to reduce the possibility and severity of a collision. While a primary tool employed in this research has been driving simulators no summary exists that critically details their use for examining these technologies. This chapter provides an introductory examination of the role of driving simulators in land transportation research for the evaluation of in-vehicle technologies designed to warn drivers of potential crashes on roadways and at intersections. Particular emphasis is directed toward identifying types of collision and intersection incursion warning technologies (CIIWT), appropriate dependent variables, driving scenarios that may be employed in simulation-based evaluations of CIIWT, and technological issues that should be addressed when installing and maintaining these systems in driving simulators.

To facilitate our understanding of these in-vehicle technologies it is necessary to first identify basic classification frameworks that define their operational characteristics. Technologies that are applied to the problems in surface transportation are classified as "intelligent transportation systems" (ITS) (Mast, 1998). These technologies can be designed for "advanced information processing, communications, sensing, and computer control" (Dingus, Gellatly, & Reenact, 1997; Mast, 1998). Due to their ubiquitous nature, ITS technologies can exist both in- and outside of vehicles (i.e., as part of the infrastructure). For example, ramp metering technology has been implemented at on-ramps to reduce travel times on highways by controlling the number of vehicles that can enter a highway at any single time and reducing congestion (see Levinson & Zhang, 2006, for a recent review of the effectiveness of ramp metering).

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Within the domain of ITS are those in-vehicle systems, commonly referred to as driver support systems (DSS), that directly support driver behavior, cognition, and perception for the purpose of improving levels of driving safety and comfort. As an example, adaptive cruise control (ACC) systems function similarly to traditional cruise control systems in that they regulate vehicle speed according to a criterion speed determined by the driver. However, ACC systems also have the capability to adapt by slowing and then maintaining a criterion time headway to a slower moving lead vehicle. In a driving simulator-based evaluation of ACC Ma & Kabar (2005) presented 18 participants with a car following task in which they were prompted to change speeds, change lanes, and navigate curves. Fifty percent of the participants were required to respond to and interact with a cell phone while all participants experienced driving with and without the use of an ACC. Results of their work indicated that ACC use was associated with improved lane keeping abilities in curves and reduced mental effort as provided by ratings on a uni-dimensional rating scale. Results of their work suggest that this DSS can be beneficial to performance and workload because, presumably, when a driver's need to monitor the environment for slower vehicles is reduced, it may free cognitive resources. These newly-freed resources can then be reinvested into lateral vehicle control. As another example, consider anti-lock brake systems (ABS) that facilitate steering and braking capabilities in inclement weather conditions by modulating brake pressure to prevent wheel lock (Evans & Gerrish, 1996; Rompe, Schindler, & Wallrich, 1987)[*].

In addition to reducing the behavioral, cognitive, or perceptual needs of drivers, DSS can also be designed to augment drivers' behavioral, cognitive, or perceptual capabilities. Recent research examining the utility of a haptic accelerator pedal supports this contention. In a driving simulator, participants were instructed to follow a lead vehicle at a constant distance at all times while performing no-DSS (baseline) or DSS drives. Participants in the DSS conditions experienced a haptic accelerator pedal that provided increasing or decreasing accelerator pedal resistance relative to the speed and distance between their vehicle and a lead vehicle. The changing resistance provided drivers with a source of information relative to the gap between vehicles, in addition to that normally available with vision alone. Results of their research indicated that the distances maintained in the DSS conditions were more consistent (Kuge, Yamamura, Boer, Ward, & Manser, 2006; Manser, Ward, Kuge, & Boer, 2005) and, when the lead vehicle slowed suddenly, driver responses to the event were faster as compared to the no-DSS baseline condition (Manser, Ward, Kuge, & Boer, 2004). See also Hjälmdahl, & Várhelyi (2004) and Várhelyi, Hjälmdahl, Hydén, & Droskóczy (2004) for allied research examining the utility of haptic accelerator pedals.

40.1.1 Collision and Intersection Incursion Technologies

There exist within DSS a subclass of devices, termed here as collision and intersection incursion warning technologies (CIIWT). These devices purport to reduce the frequency and severity of motor vehicle crashes. They are designed to accomplish this goal by providing drivers with a warning within or outside a vehicle cockpit regarding an imminent collision (i.e., collision warning technology). These devices can also accomplish this goal by signaling to drivers that they have entered an intersection illegally (e.g., violating a red light) or legally (e.g., stop at a stop sign and then proceed) but that the situation is unsafe due to, for example, an approaching vehicle (i.e., intersection incursion warning technology). This simple description trivializes the complexity of CIIWT conceptualization and operation. Conceptually, these systems are consistent with the notion of a field of safe travel (see Gibson & Crooks, 1938) in that they notify a driver of lateral and longitudinal incursions into this field from objects that approach a driver's vehicle (e.g., vehicles, pedestrians) or from objects that a driver approaches. Conveying the degree of an imminent collision or intersection incursion is often accomplished by scaling the warning signal such that the frequency, tone, or intensity of warning increases as a collision becomes more certain. These systems have been designed to operate in roadway and intersection environments, urban and rural areas, and can often warn drivers of both vehicle-to-vehicle (e.g., sideswipe, forward collision, or rear collision) as well as vehicle to non-vehicle collisions (e.g., pedestrians). Operationally, these systems can employ sophisticated laser, radar, or acoustic sensors (Bellomo-McGee, 2003) that are integrated within a vehicle to detect the distance and speed of surrounding objects and to determine if a collision may occur. Similar sensors can be integrated within the roadway infrastructure to detect the presence, location, and speed of vehicles. When vehicle or infrastructure-based sources of information are coupled with algorithms to calculate the possibility and timing of a collision or intersection incursion, they can inform a driver with warnings via audition (e.g., tones, instructions), haptics (e.g., active accelerator pedals, vibrotactile seats), or vision (e.g., text or icons on a heads-up display, on dashboards, and on signs placed in the environment) (see Pierowicz, Jocoy, Lloyd, Bittner, & Pirson, 2000; Campbell, Richard, Brown, & McCallum, 2007 for a review of modalities and associated warning characteristics).

There exist several types of CIIWT that can be differentiated according to the primary location of the technology. The technology employed in these systems is based within a vehicle, within the transportation infrastructure, or, more recently, is a combination of vehicle and infrastructure. Table 40.1 provides a brief description of common CIIWT, relative to the location of the system. An example of a vehicle-based CIIWT would include forward collision warning systems (FCW). Commonly, a FCW consists of a radar sensor embedded in the front bumper of a vehicle that detects the distance to a lead vehicle. The distance information can then be combined with vehicle speed information to generate a value that reflects the criticality level (e.g., dangerousness, potential for a collision) between the two vehicles. The FCW can then provide a simple auditory warning (e.g., beep) or illuminated icon when a driver's vehicle detects that the proximity of the lead vehicle is too close (Pierowicz, Jocoy, Lloyd, Bittner, & Pirson, 2000). Rear collision warning (RCW), side collision warning (SCW), and lane change warning (LCW) systems operate in a similar manner.

Transportation infrastructure-based systems consist of sensing and warning equipment that resides in the environment, typically installed along roadways or at intersections. These systems can help improve levels of safety by providing information or warnings to drivers to help them make better driving decisions. For example, previous research has indicated that a factor contributing to high rates of crashes at some rural thru-stop intersections[†] is the ability of drivers on a minor roadway, who are controlled by a stop sign, to estimate accurately the gap between approaching vehicles on a

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[*] Electronic stability control systems that control wheel speed can also facilitate vehicle dynamics capabilities that may result in a decreased propensity for collision. However, these systems are not addressed here because they are primarily designed to mitigate vehicle loss of control (e.g., skidding).

[†] A rural thru-stop intersection is characterized here as a highway segment (e.g., two lanes in each direction with a separating median) that is intersected by a minor roadway (e.g., two-lane roadway). Traffic on the highway segment has the right-of-way whereas traffic on the minor roadway is controlled by a stop sign.

TABLE 40.1 Primary types of collision and intersection incursion warning technologies

Technology Location	CIIWT	Purpose	Collision Mitigation
Vehicle-based	Forward Collision Warning (FCW)	Warn a driver the gap between their vehicle and a lead vehicle is below a safety threshold.	Collision to the front of driver's vehicle.
Vehicle-based	Rear Collision Warning (RCW)	Warn a driver the gap between their vehicle and a following vehicle is below a safety threshold.	Collision to the rear of driver's vehicle.
Vehicle-based	Lane Departure Warning (LDW)	Warn a driver they are exceeding their lane boundary.	Sideswipe collision to each side of vehicle.
Vehicle and Infrastructure-based			
Vehicle-based	Roadway Departure Warning (RDW)	Warn a driver they are exceeding the roadway boundary.	Single vehicle roadway departure.
Vehicle and Infrastructure-based			
Vehicle-based	Lane Change Warning (LCW)	Warn a driver when a vehicle is occupying the lane into which they want to change.	Sideswipe collision to each side of vehicle.
Vehicle-based	Side Collision Warning (SCW)	Warn a driver when the gap between their vehicle and a vehicle approaching from the side is below a safety threshold.	Collision to the left or right side of a driver's vehicle.
Infrastructure-based	Intersection Collision Warning (ICW)	Warn a driver who is approaching an intersection about the presence of vehicles on the intersecting roadway.	Left turn across path.
Vehicle and Infrastructure-based		Warn a driver at an intersection about the presence of approaching vehicles.	Entry without adequate gap.
			Violation of traffic control signal.
			Violation of traffic control signal.

major intersecting roadway (i.e., highway) (Chovan, Tijerina, Pierowicz, & Hendricks, 1994; Najm, Koopmann, & Smith, 2001). An inability to accurately determine approaching vehicle gaps may lead drivers to select gaps that do not support safe intersection crossing behaviors. In an effort to address this situation researchers have developed an infrastructure-based system, termed "intersection decision support system" (IDS) (see Creaser, Rakauskas, Ward, Laberge, & Donath, 2007; and Laberge, Creaser, Rakauskas, & Ward, 2006, for an extended presentation of IDS technology), that can inform drivers on a minor roadway of the gaps between vehicles on a major roadway. The system consists of a series of sensors placed along a section of a major roadway (i.e., highway) that detect the presence and speed of vehicles. See Figure 40.1 (Web Figure 1 for color version) for a depiction of the sensor layout at an example intersection. This information is then forwarded to a central computer near the intersection that can provide information to a driver via an illuminated variable message sign. See Figure 40.2 (Web Figure 2) for a depiction of an example variable message sign presenting unsafe gap information. This is known as a cooperative intersection collision avoidance system - stop sign assist (CICAS-SSA). Creaser, Rakauskas, Ward, Laberge & Donath (2007) examined the utility of four IDS conditions for both younger and older drivers during day- and nighttime conditions in a driving simulator. In their study, participants crossed a simulated rural thru-stop intersection twice in each of five conditions: A stop-sign condition which served as a baseline against which the other conditions were compared, and four IDS conditions that presented signs to drivers waiting to cross on a minor roadway with differing levels of dynamic traffic information about vehicles on a major roadway (each of the four sign conditions was presented with the baseline stop sign condition). Results of their work indicated that the use of all tested IDS signs was associated with drivers accepting gaps that were significantly larger than the stop sign only condition. However, IDS signs that provided gap (e.g., time-to-arrival and gap warnings) and advisory information were associated with the best performance as compared to the signs that did not provide this information.

Vehicle and transportation infrastructure-based CIIWT can share information between in-vehicle and infrastructure-based systems. For example, research efforts are underway to develop and evaluate a cooperative intersection collision avoidance system that provides an in-vehicle warning to a driver if there is a potential they will violate a traffic control signal or stop sign. This CIIWT collects information from the infrastructure to determine if a signal is in a prohibited phase and collects information from a vehicle to determine if it is turning or moving through an intersection. If the maneuver is prohibited, the CIIWT wirelessly transmits a signal to an in-vehicle display to warn a driver of a prohibited intersection incursion. While information regarding the utility of this system is not available at this time, it is hoped that this technology can reduce the rate of collisions at intersections due to prohibited incursions.

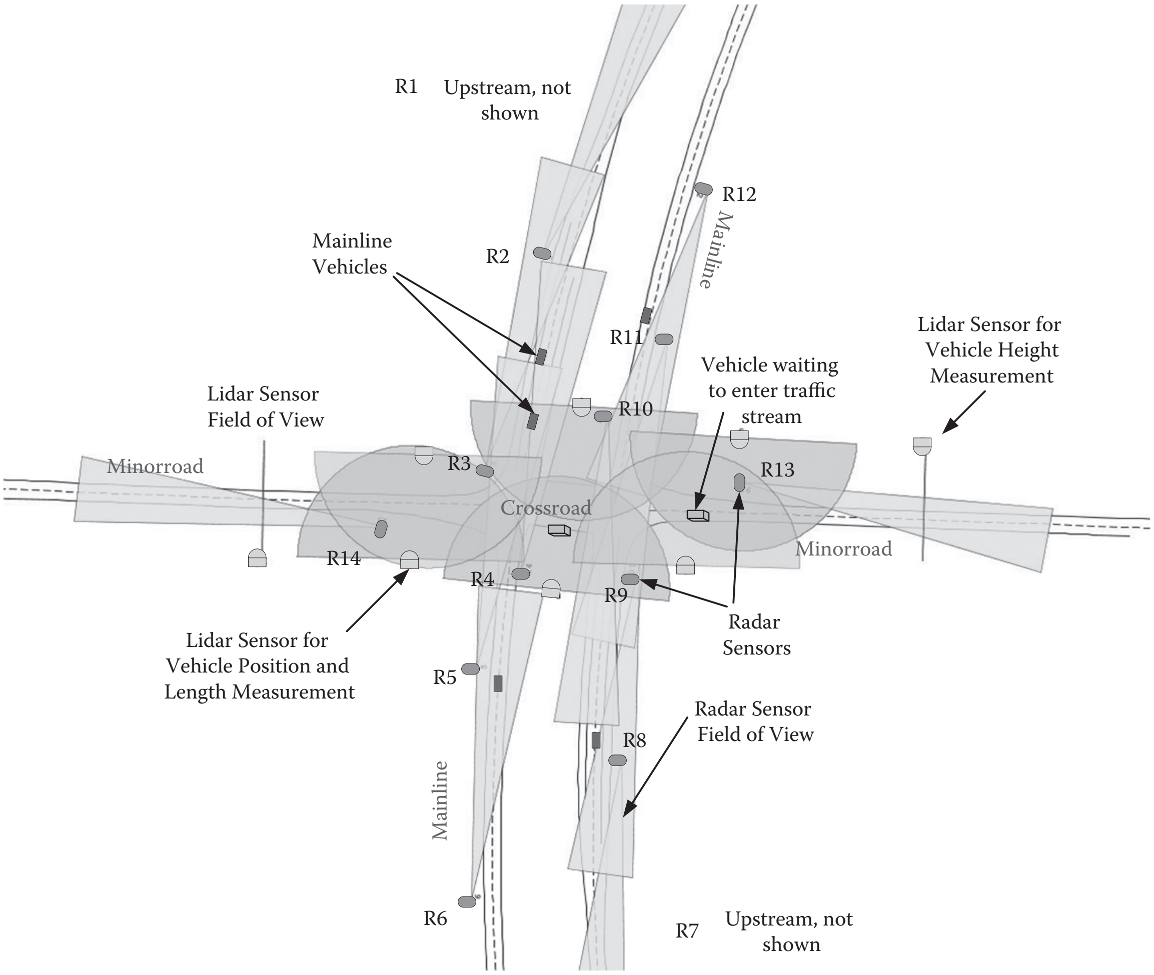

FIGURE 40.1 Plan view of an instrumented rural expressway intersection. Sensors on the mainline roadway (north and south in the figure) are radar which provides range, altitude, rate, and azimuth of vehicles relative to the sensor. Sensors on the minor roadway are lidar (i.e., light detection and ranging), which provide range to vehicles.

As suggested by the current discussion, CIIWT are intended to reduce the frequency and severity of motor-vehicle crashes or intersection incursions by providing drivers with warnings within or outside a vehicle. CIIWT are identified here as one of type of a broader class of systems that are intended to support drivers within the domain of ITS technology.

40.1.2 Collision and Intersection Incursion Scenarios

In light of the notion that many CIIWT evaluated in driving simulators may be deployed in real-world situations, it is necessary to optimize the ability to generalize results between real-world and driving simulator settings. One method for increasing generalizability is to include in driving simulator evaluations those real-world scenarios in which CIIWT are expected to operate. The purpose of this section is to identify and describe the primary roadway and intersection driving scenarios contributing to high crash rates that prototypical and existing CIIWT have been designed to address. Previous research efforts (Keifer et al., 1999; Kiefer et al., 2003; Najm & Smith, 2007; Pierowicz et al., 2000) have collectively identified six basic driving scenarios which include rear-end (RE), lane departure (LD), left turn across path (LTAP), entry without adequate gap (EWAG), violation of traffic control (VOTC), and violation of traffic control signal (VOTS). The rear-end scenario occurs most often in urban environments and is characterized by a subject vehicle (SV) that crashes into the rear of a lead vehicle (LV) due to a variety of reasons including inattentive driving, distracted driving, poor visibility, aggressive driving habits, tailgating, and cut-in behaviors by a vehicle from an adjacent lane (Keifer et al., 1999). Mitigation of crashes within this scenario is primarily addressed by FCW systems that warn a driver of events that may occur in front of their vehicle (see Figure 40.3, location 1 for a depiction of this scenario). The lane change scenario is characterized by a SV that steers into an adjacent lane which is occupied by another vehicle (see Figure 40.3, location 2). This scenario is common to both urban and rural environments in which there exist two lanes of traffic moving in

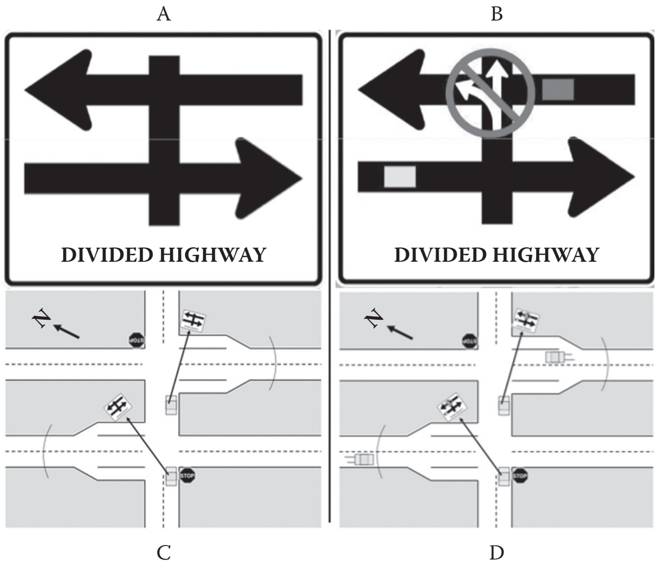

FIGURE 40.2 Two CICAS-SSA variable message signs presenting gap and warning information to a driver positioned at a stop sign. The sign would be presented to drivers on the minor roadway only. In the example, a driver would be attempting to cross a highway with two lanes of traffic in each direction separated by a median. The sign presented in Figure 2A indicates to the driver on the minor road that no vehicles are present on the roadway, as depicted in Figure 2B. The white icon (presented as yellow in experiments) in Figure 2C indicates that, for the near lanes of traffic, an approaching vehicle has entered a zone where the gap should be accepted with caution (zones are marked by a curved line). The same sign indicates that, for the far lanes of traffic, an approaching vehicle has entered a zone where the gap should not be accepted. This is depicted as a white circle and diagonal line (presented as red in experiments).

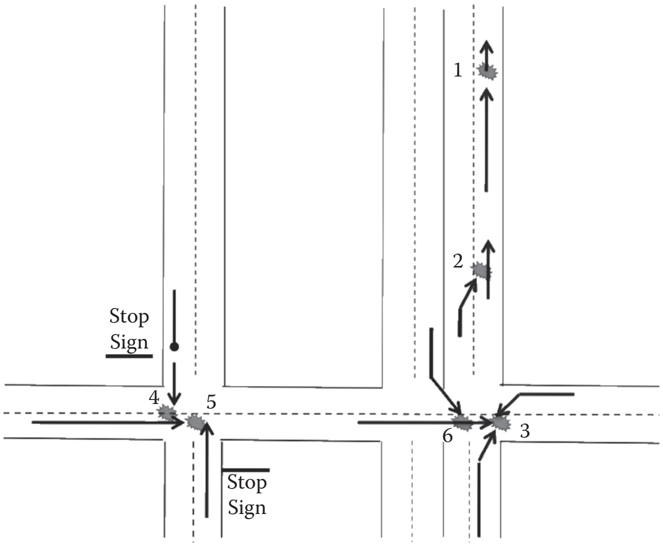

FIGURE 40.3 Roadway and intersection crash scenarios. The six individual crash scenarios are identified by numerals 1–6.

the same direction. CIIWT technologies such as lane departure warning (LDW) are best suited to address these crash scenarios due to their ability to identify and warn against events occurring laterally to the SV. The final four scenarios are indicative of intersection incursions (see Pierowicz et al., 2000 for full descriptions of these scenarios). LTAP is characterized by a SV that has the right-of-way (i.e., green-light) at a signalized intersection and is presented with an opposing vehicle turning left that has not yielded (see Figure 40.3, location 3). EWAG is depicted in Figure 40.2, location 4 and occurs when an opposing vehicle stops at the traffic control device (stop sign) and then proceeds through the intersection (to turn left, right, or proceed straight) without allowing an adequate gap between their vehicle and the SV. VOTC occurs when an opposing vehicle violates a traffic control device (e.g., runs a stop-sign or a red light) and is struck by the SV that has the right-of-way from the left or right (see Figure 40.3, location 5), while VOTS is the opposite (i.e., SV violates a traffic control device and strikes opposing vehicle) (see Figure 40.3, location 6). Note, that while these scenarios occur frequently in urban environments they are also not uncommon (especially LTAP, EWAG, and VOTC) in rural environments that contain low-cost traffic control devices (i.e., stop signs) or no devices at all. FCW are one type of CIIWT to deploy at intersections to address LTAP, EWAG, VOTC, and VOTS scenarios due to the fact that events primarily occur in front of the SV. However, more advanced intersection collision warning systems such as those that track individual vehicle movements, typically through the use of vehicle-based global positioning satellite technology, also present an effective method to reduce collisions at intersections.

40.2 Characteristics of Design

The overall design of a CIIWT depends predominantly on its intended purpose. However, the operation can also be defined based on underlying design characteristics that are exhibited to a greater or lesser extent for most CIIWT. It is important for driving simulator users to be aware of these design characteristics in order to integrate these systems into driving simulators adequately and to be prepared for the resources required for integration. Note that while all CIIWT presented earlier can be integrated into most driving simulators, the design characteristics of each system will allow for easier or more difficult integration. In addition, users should carefully consider each of the design characteristics because their manipulation (i.e., they are independent variables) can significantly influence CIIWT effectiveness. Given that each characteristic can have a greater or lesser influence on CIIWT effectiveness, each exists along a continuum. The following section summarizes each of the primary characteristics of design along with a description of the ease of integration into a driving simulator.

A characteristic of all CIIWT is system action/initiation, which refers to the degree to which a system will act or initiate warnings based on information it has received (e.g., vehicle presence, distance to vehicle) or generated (e.g., time headway, time to lane crossing). On one end of the continuum a CIIWT can warn when it detects an imminent collision such as when a

FCW provides short tones to warn a driver they are approaching a slower vehicle (Kiefer et al., 1999) or a LDW that warns a driver when they are exceeding lane boundaries (Houser, Pierowicz, & Fuglewicz, 2005). These warnings simply indicate to a driver they should act and are the easiest to integrate into a driving simulator due to their simple technological features (e.g., distance-detection device and a system for producing a warning sound). The middle of the action/initiation continuum represents those CIIWT that are increasingly powerful and omnipresent. Versions of CIIWT have begun to combine warnings along with information regarding the criticality of the situation, such as a FCW that indicates the time in seconds to a lead vehicle (Alkim, Bootsma, & Looman, 2007). The provision of warnings and information allow a driver to better assess the situation and select an appropriate response, essentially indicating to the driver that: a) they should act, and b) how quickly they should act. These CIIWT can also be easy to integrate into a driving simulator due to the relatively simple technology required. At the end of the system action/initiation continuum are those most recently developed CIIWT that incorporate automated vehicle control. While these systems often employ warnings and information from the middle and the opposite end of the system action/initiation continuum they can also unilaterally initiate vehicle responses, augment driver behaviors, or attenuate driver behaviors. For example, some current model automobiles are equipped with brake assist systems that can detect a critical scenario developing in front of their vehicle through radar sensors using FCW. These can warn and inform the driver of the urgency of the scenario through a series of increasingly frequent tones, and can initiate actions to reduce or eliminate the criticality of the situation with or without driver awareness by either slowing a vehicle through engine braking or, in highly critical situations, through near-threshold braking. As evidenced by these examples CIIWT can range from simple warnings to warnings that are coupled with rich information and extensive vehicle actions.

The varying level of complexity within this continuum raises important issues that must be considered by users of driving simulators. First, as CIIWT system complexity increases along the system action/initiation continuum the effort and associated costs for installation, programming, and long-term support will also increase. For example, CIIWT on the latter end of the system action/initiation continuum can be difficult to integrate into a driving simulator due to the need for equipment that can implement actions. In the example presented above it would be easy to "program" a simulator to detect a critical scenario and it would be easy to output a warning signal to a speaker system. However, to initiate an action such as near-threshold braking, a simulator would most likely need a modest motion-base system to accurately depict vehicle dynamics and subsequent braking[*]. The effort and cost associated with the installation and use of a partial or full motion-base simulator are not insignificant. As a result, the simulation user must determine if adequate resources are available to support a desired experimental evaluation. Second, as CIIWT system complexity increases there will be a corresponding increase in the complexity of experimental parameters to be addressed. These may include the type experimental design, range of dependent variables and, due to longer periods of time to perform an evaluation, physical fatigue, visual fatigue, and boredom will also need to be addressed. The system action/initiation continuum and the examples presented provide tentative support for the notion that when designing a driving simulator-based experiment that will employ a CIIWT, or when integrating a CIIWT into a driving simulator, it will be necessary to identify where on the system action/initiation continuum the CIIWT system exists. This will allow driving simulator users to more accurately determine the true effort and cost associated with CIIWT system installation and operation and to account for essential experimental variables.

Temporal/distance system activation (TSA) represents the time and/or distance at which a CIIWT initiates a warning or action after event detection. The endpoints of this continuum are simple from a conceptual standpoint; one end is essentially "zero time" in which a system is activated simultaneously with, or just previous to, an event while the opposite end represents system action/initiation presented significantly before an event (see Figure 40.4 for a depiction of this continuum relative to time and distance). Practically, the endpoints can be difficult to assess. For example, the ability of a CIIWT to determine when a collision will occur can be influenced by the capabilities of a sensor (e.g., sensors that detect vehicles, intersections, pedestrians), sensor type (e.g., radar, laser, lidar, acoustic), and additional factors that may introduce non-constant variables into sensor capabilities or into the algorithms employed to calculate when an event would occur (e.g., wireless transmission delay between sensor and vehicle, weather conditions that may interfere with sensor sensitivity). In addition, while oftentimes a determination of

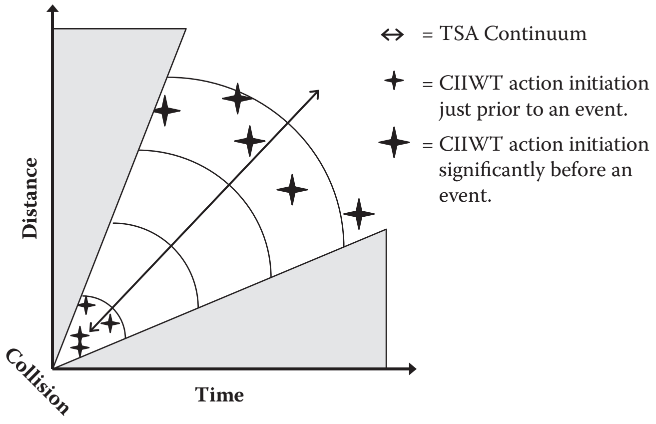

FIGURE 40.4 Temporal system activation continuum for CIIWT which depicts the when a system initiates an action after event detection. Note that the shaded areas represent time and distance combinations that are normally not experienced in typical driving situations.

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[*] Note that braking dynamics can be emulated in a driving simulator without a partial or full motion-base system. However, to promote driver behaviors that are similar or identical to real-world situations it may be necessary to allow drivers to experience realistic sensations of braking.

the "moment" an event may occur (e.g., collision, intersection incursion) is calculated with precision, some algorithms include a confidence variable which considers the degree to which the information gained from the sensors may be accurate or reliable. If the information is deemed to be of low accuracy or reliability, a system may delay a warning or action until the confidence value exceeds a predetermined threshold (i.e., accuracy or reliability has improved). In addition, if one type of distance sensor can detect objects at greater range than another it is reasonable to expect that a warning could be provided to drivers at an earlier stage.

Within this continuum researchers must also be cognizant of the collision warning timing presented to drivers due to the notion that inappropriately-timed warnings may be associated with a decrease in driving safety (see McGehee & Brown, 1998). Research conducted in a driving simulator has indicated that early warnings are more beneficial than late warnings (or no warnings) for both distracted and undistracted drivers (Lee, McGehee, Brown, & Reyes, 2002). However, as indicated by Weise & Lee (2004), great care must be taken when alerts are paired temporally. Their research found that when a non-collision alert (email notification) was presented 1000 ms previous to a collision warning, driver responses were enhanced while the same warning presented only 300 ms in advance of the collision warning degraded driver response, presumably due to dual-task interference. To incorporate into driving simulation experiments CIIWT systems that are truly representative of actual systems, driving simulator users must assiduously define the operational characteristics of a CIIWT system's endpoints along the TSA continuum and, if a system is to be deployed in the real-world, researchers must consider carefully the warning timing functions (see Campbell et al., 2007 for a review of multiple warning signal prioritization and integration).

CIIWT systems along the TSA continuum are equally easy to implement into a driving simulator technologically because the underlying equipment that will provide a warning immediately prior to a collision, and which will provide a warning in advance of collision, will be identical, or quite similar. The difficulty in implementing systems with regard to the TSA continuum is the increased amount of programming effort that may be required to develop advanced algorithms on which the warnings are based.

The physical location in which a system has been designed to operate is termed here as geospatial system activation (GSA), with urban and rural environments composing opposite ends of the associated continuum. Given that CIIWT are typically designed to address specific events and that these events typically occur in specific environments, it is important for driving simulator users to couple events and environmental characteristics to accurately assess the true utility of a CIIWT relative to its intended design. As an example, recent work has indicated that thru-stop crashes, which are those crashes in which drivers on a minor road attempt to cross a median of a major road (e.g., highway) and misjudge the gap afforded by approaching vehicles, are a significant problem in rural environments (Chovan et al., 1994; Najm et al., 2001). It is not surprising that CIIWT designed to mitigate thru-stop crashes consider the factors specific to this event (e.g., speed, sight distance, power connections for remote data collection along the major road, etc.) and that these factors are defined by the location (see Figure 40.3) in which the crash type exists. This notion supports the contention that in order to impartially evaluate a system, driving simulators must account for the environment in which the CIIWT will be deployed and account for the primary factors specific to the crash type to be mitigated. Implementing CIIWT in a driving simulator that is specific to each end of the GSA continuum will require similar levels of effort and cost due to the similarity in the underlying technology and programming requirements.

The characteristics identified previously related to CIIWT functionality; however, it is also important for driving simulator users to consider the physical aspects that are associated with the integration between a CIIWT and driving simulator. One aspect relates to the location of the CIIWT hardware and software components. A vehicle-based CIIWT may require minimal effort and hardware to integrate into a driving simulator. For example, a simple FCW implemented in a driving simulator could consist of gathering time headway data to a lead vehicle via software, programming logic to determine the time headway threshold at which a warning will be activated, a digital to analog converter to generate an analog warning signal, and a buzzer that can receive a signal and provide a warning. Integrating this type of CIIWT into a driving simulator should be relatively easy. In contrast, there are CIIWT that are physically complex and, as a result, may require significant efforts to replicate in driving simulators. For example, the infrastructure-based CICAS CIIWT described previously requires that a) the position and speed of all vehicles traveling through an area surrounding an intersection be identified; b) that gaps between all vehicles and between the vehicles and the intersection be calculated; and c) that this information be presented on a simulated variable message sign. While each of these three activities within a driving simulator is possible, they can require substantial programming efforts and, as a result, will be significantly more challenging to implement.

A second aspect relates to the level of CIIWT integration within a vehicle, environment, or infrastructure. A system that requires a greater degree of integration will be associated with an increase in driving simulator programming and hardware installation effort. For example, the integration of a vehicle-based rear collision warning system (RCW) may include a simple distance sensor and speaker to provide a warning. However, more complex systems that combine FCW, RCW, LDW, and intersection incursion warnings into a unified vehicle and infrastructure-based CIIWT will require extensive intra-system, vehicle, environment, and infrastructure coordination and integration.

The physical mechanism that will deliver a warning to a driver is a final aspect that should be considered during installation and continued operation of a CIIWT within a driving simulator because of the potential technical hurdles and costs that may need to be addressed. A mechanism that can provide a discrete auditory or visual warning (e.g., a tone or a flashing light) will require minimal integration and cost while a system that provides feedback via a vibrotactile seat (Ho, Reed, & Spence, 2006) or heads-up display (Caird, Chisholm, & Lockhart, 2008) will require significant costs due to the required equipment purchases and integration costs.

The characteristics of functionality and physical aspects can vary greatly between differing types of CIIWT. For those CIIWT systems that are functionally and physically uncomplicated the development and installation of these devices into driving simulators will be tractable. However, CIIWT that are complicated in terms of warning initiation type, warning initiation timing, geographic location of system components, and physical design may present formidable obstacles to the implementation, continued operation, and use of CIIWT within driving simulators unless simulation users and engineers anticipate these issues.

40.3 Simulation and Experimental Designs for CIIWT Research

In order for an examination of the utility of CIIWT within driving simulators to yield valid, reliable, and veridical results, researchers should consider a range of simulation and experimentation issues. The purpose of this section is to identify several of the prominent issues to be considered when examining CIIWT. However, the reader is encouraged to expand the scope of their understanding by reviewing allied chapters within this *Handbook* that address scenario selection, independent and dependent variables (e.g., the chapter by McGwin), and various aspects of fidelity (e.g., simulation, traffic, physical, perceptual, and behavioral; see the chapters by Greenberg, Ranney, Andersen, & Angell) because of the significant role they may also play in conducting CIIWT research within a simulation environment.

40.3.1 System Selection

Generalization (Chapanis, 1988; Schmidt & Lee, 2005) is arguably one of the more prominent considerations when employing a driving simulator for CIIWT. Generalization is the degree to which research results can be expected to extrapolate to real-world scenarios or, relative to the current topic, how well research results obtained from studies employing driving simulators that examine the efficacy of CIIWT can predict the utility of the same technologies when they are deployed in real-world environments. Global methods to increase generalization of research results are provided elsewhere in this *Handbook* (e.g., see the chapter by Hancock and Sheridan). Specific to CIIWT, the most promising method is to equate the psychological processes between the testing and real-world environments (Kantowitz, 1992; Schiff & Arnone, 1995). However, as mentioned previously (Manser & Hancock, 1996), the nature and extent of the primary psychological processes in real-world environments has yet to be established adequately. How then, can users of driving simulators who are examining CIIWT promote generalizability? Due to the notion that a highly realistic environment can be expected to contain a greater number of veridical psychological processes than a non-realistic environment, a primary technique that can be employed is to increase realism. Realism is the degree to which testing environments represent the real world. Increasing the realism of driving environment simulation-based research can be accomplished by several methods that can be described according to vehicle and environmental constructs. Realism elements within the vehicle construct should include accurate representations of vehicle dynamics, (e.g., steering, acceleration, and deceleration), highly functional vehicle cab, and a full range of CIIWT characteristics to be investigated. Relative to the environment, realism elements should include high-resolution images, wide field of view to promote an accurate sense of speed, presentation of driving scenarios that are based on comparable real-world scenarios (e.g., collision, intersection, vehicle incursion), and depiction of realistic traffic flows (e.g., vehicle size, traffic density, gap presentation, and vehicle speed) that are representative of those appearing in real-world environments under consideration. Although technically difficult, an attempt should also be made to include salient real-world elements specific to the scenario and/or CIIWT to be examined (e.g., pedestrians, buildings, traffic signaling, night/day conditions).

40.3.2 Dependent Variables

A determination of the veridical utility of a CIIWT begins with an identification of dependent variables that are supported by a sound rational. Previous work in an allied area that examined in-vehicle information systems (Green, 1994) provides a sound rational for the selection of dependent variables within driving simulator-based evaluations (traditional dependent variables employed in driving simulator work can be found elsewhere in this *Handbook*; see the chapters mentioned above). Adapted from that work, the following criteria for dependent variable selection relative to the examination of CIIWT are suggested: (1) Dependent variables should be directly related to the underlying research hypothesis being considered; (2) dependent variables should be of sufficient sensitivity to detect differences due to the use or inclusion of a CIIWT; (3) dependent variables that increase risk or embarrassment for drivers should not be included; (4) dependent variables that add to the cost and complexity of experiments should be assessed to determine both if they can be included and the degree of their worth; (5) dependent variables should be of sufficient simplicity so that they can be analyzed effectively; (6) metrics must exhibit repeatability in that they can reliably detect performance differences; (7) metrics should have been validated in real-world and driving simulation settings previous to their inclusion in driving environment simulation experimentation; and (8) metrics should be appropriate to the driving scenario under examination (e.g., lane deviation metrics should be employed when examining an in-vehicle lane departure warning system).

AU: I think the list of dependent variable selection criteria is substantial enough to warrant list formatting. Please review.

In light of these "guidelines" governing the selection of dependent variables, what then are the dependent variables that should be employed when examining the utility of CIIWT? The answer to this question is not straightforward. The utility of a

CIIWT can be measured in terms of safety, which is dictated by changes in human performance. How a CIIWT may influence driver stress is also an important consideration given the potential relationship between stress and performance. In addition, the degree to which a system is usable can significantly impact drivers' perceptions of a CIIWT and subsequent system use. The following sections identify some potential dependent variables within the constructs of performance, stress, and usability that may be necessary in order to gain a broad understanding of the true utility of a CIIWT.

40.3.2.1 Performance Construct Dependent Variables

Dependent variables within the performance construct relate to a vehicle's *input* devices (i.e., steering, braking, and acceleration) that reflect direct driver control of a vehicle and relate to resultant vehicle *output* (i.e., often measured in safety margins such as time-to-contact or time headway) as a result of CIIWT use. These variables can provide an understanding of the utility of a CIIWT with respect to driver performance. Within the input and output classifications, dependent variables can be further categorized according to task type (adopted from Green, 1994) which include: 1) primary task (i.e., the main task of the driver which is to control a vehicle), 2) CIIWT task (i.e., the task of interacting with the CIIWT and associated performance changes), and 3) overall task which will include performance metrics not associated with direct vehicle or CIIWT control (e.g., eye gaze behaviors). Input and output classification and task type can serve as the basis from which dependent variables for CIIWT research in driving simulators can be selected. A list of potential input and output dependent variables is presented in Tables 40.2 and 40.3, respectively.

Many of the input and output dependent variables that can be employed to assess the utility of a CIIWT have been identified previously (Green, 1994; Keifer et al., 2003); however, several variables identified in Tables 40.1 and 40.2 have been developed and employed successfully more recently and deserve further consideration. Consistent with the selection criteria that recommends dependent variables exhibit sensitivity and in light of the significant impact a CIIWT can have on event detection and response, researchers have employed input dependent variables that identify stages of perception-response times (see Olson, 2001 for an extended description of perception-response stages) that are indicative of CIIWT efficacy. The four perception-response stages thought to exist, and as they apply to CIIWT, include detection (i.e., first recognition of an object or event such as an approaching vehicle), identification (i.e., first determination that an object or event is a threat), decision (i.e., the moment an appropriate response to the threat is identified such as deciding to apply a vehicle's brakes), and response (i.e., the moment the appropriate response is executed such as initiating movement of the lower leg to begin the braking response). An understanding of perception-response stages and their application to CIIWT evaluations offers unique insights into event detection and identification, into the selection of responses that are appropriate for addressing a developing situation, and into whether these potential benefits result in faster responses and decreased potential for crashes. For example, research that examined the utility of haptic feedback (i.e., accelerator pedal force changes) as an information source to drivers (i.e., employed for detecting changes in the gap between a driver's vehicle and a lead vehicle) (Manser et al., 2004) decomposed the primary driver response of pedal movements into their principle components consistent with human

TABLE 40.2 Performance dependent variables for driver input controls (adapted from Green, 1994).

Task Type	Control Direction	Dependent Variables
Primary (i.e., driver control of vehicle)	Lateral	– steering wheel, movements per unit of time – steering wheel, reversals – steering wheel, reversal rate – steering wheel, action rate – angular wheel, position change average – angular wheel, position change standard deviation
	Longitudinal	– throttle position, average – throttle position, standard deviation – brake application, count – brake pressure/position, average – brake pressure/position, standard deviation
CIIWT (i.e., driver control and response to non-vehicle tasks)	System Utility (detection performance)	– accelerator reaction time – accelerator movement response time – accelerator movement time headway – brake response time – brake response time headway – max brake pedal pressure/position – 85th percentile brake pedal pressure/position – transition time between accelerator pedal release and brake pedal activation
Overall	Vision	Frequency and duration of glances to the: – road – mirrors, HVAC, display cluster – CIIWT (if visible and requiring driver interaction)

TABLE 40.3 Performance dependent variables for vehicle output controls (adapted from Green, 1994).

Task Type	Control Direction	Dependent Variables
Primary (i.e., vehicle output)	Lateral	– lateral, deviation mean – lateral, deviation mean absolute – lateral, deviation standard deviation – lateral, acceleration – lateral, yaw rate – lateral, yaw angle – lateral, yaw acceleration – lane deviation count – percent and total time outside lane – steering entropy
	Longitudinal	– speed, mean – speed, standard deviation – acceleration/deceleration, average – accelerations/decelerations, exceeding a g criterion – headway mean, to lead vehicle – headway standard deviation, to lead vehicle
CIIWT (i.e., driver control and response to non-vehicle tasks)	System Utility (detection performance)	– time to lane crossing – time to contact to lead vehicle – time to arrival at intersection – coherence to a lead vehicle – modulus to a lead vehicle – delay to a lead vehicle
Overall		– crashes – near misses

motor control measures of time and speed (e.g., reaction time, response time, transition time, movement time) (Schmidt & Lee, 2005). These principle components then served as input dependent variables that identified driver "decisions" and "responses". In this work, participants drove through a simulated environment, once with the use of the haptic accelerator pedal and once without, and were tasked with following a lead vehicle at a constant, close, and safe distance at all times. Throughout the drive the speed of the lead vehicle gradually increased and decreased; however, while an in-vehicle secondary device distracted drivers, the lead vehicle slowed suddenly. Results of their work indicated the use of a haptic accelerator pedal could facilitate event detection as indicated by significantly faster reaction times to the sudden braking situations. Although this technology is not a collision warning system the utility of these metrics for understanding perception-response time and associated information processing can be applied easily to CIIWT evaluations.

Traditional output dependent variables for CIIWT research have included metrics that indicate the degree to which safety margins (e.g., time-to-contact) (Keifer et al., 2003) are violated relative to the use or non-use of a CIIWT. Non-traditional output dependent variables such as coherence, amplification, and delay (Brookhuis, De Waard, & Mulder, 1994: Ward, Manser, De Waard, Kuge, & Boer, 2003) can also be useful for identifying performance changes as a result of system use. Coherence represents a correlation between a lead and following vehicle's speed profiles that is reflective of the accuracy of drivers' speed adaptations (i.e., drivers' ability to maintain a safe and constant distance between their vehicle and a lead vehicle). Modulus represents the degree to which a participant over- or underestimates the maximum and minimum speed of a lead vehicle. The postponement in time between a lead vehicle and following vehicle speed change is termed delay. Research that employed a car following task in a driving simulator found that coherence, modulus, and delay (Ward et al., 2003) are sensitive to changes in driver performance due to the use of a continuous information source (via a haptic accelerator pedal identified earlier) that provides information relative to the gap between a driver's vehicle and a lead vehicle.

40.3.2.2 Stress Construct Dependent Variables

Decreased levels of driver stress due to positive interactions with a CIIWT may greatly facilitate an overall positive impression of a system and promote continued use. The selection of dependent variables that describe an association between stress and CIIWT use can be difficult due to the notion that changes in stress levels may occur over long periods of time as compared to the relatively succinct support offered by a CIIWT. This section summarizes metrics of stress that are common to evaluations of CIIWT and that could be employed in future evaluations. As a result, there is the potential that measures of stress may reflect changes due to factors not associated with system use. However, traditional stress measures may provide utility if researchers bear in mind the potentially imperfect ability of these metrics. One method for evaluating driver stress is through the use of questionnaires. Mental workload, a surrogate measure of overall mental stress, can be measured relatively quickly with the Rating Scale Mental Effort (RSME) developed by Zijlstra (1993). The RSME consists of a univariate scale on which drivers indicate their perceived level of mental effort associated with the driving task. It has been shown to be a good measure of mental effort in cases where a secondary task is presented and may prove helpful in determining general increases/decreases in mental effort due to CIIWT use. The Mood Adjective Checklist (MACL) can be employed to measure driver affective mood state (mood stress) (Matthews, Jones, & Chamberlain, 1990). In this self-report measure drivers indicate their level of feeling for each of 29 mood adjectives on a four-point scale that are then combined to assess the composite mood factors of hedonic tone (cheerful, contented, satisfied), tension (anxious, jittery, tense, nervous), and vigor (active, energetic, alert, vigorous). These measures can also be combined with more traditional measures, such as the NASA-TLX (Hart & Staveland, 1988), to provide confirmatory evidence of changes in mental effort.

Psycho-physiological metrics of driver stress are involuntary in that they respond to stress without conscious control or without subjective bias on behalf of participants. Galvanic skin response (GSR) is a metric of arousal/effort that measures changes in skin conductance levels as a result of perspiration generated from increased stress levels. GSR is typically collected via sensors placed on the first and second fingers of a driver's hand. Heart rate variability (HRV) is quantified in terms of beats per minute. 10 Hz sinus arrhythmia measures changes in the profile of heart beats in response to workload/effort (Brookhuis & De Waard, 2001).

40.3.2.3 Usability Construct Dependent Variables

Designers of CIIWT should be aware of the "usability" of their systems because poor usability could lead to dissatisfaction and non-use, which would negate the potential benefits afforded by a system. This section summarizes common metrics that could be employed to evaluate system usability. Usability is the degree to which drivers accept, understand, learn, and interpret a system. The intangible factors of usability are made tangible through answers provided on questionnaires exploring a range of diverse issues such as how drivers perceive the usefulness of a system; how satisfied they are with a system; to what degree do drivers trust a system to operate correctly; whether the system promotes improved performance; and how easy a system is to learn and understand. While the use of many questionnaires can provide a robust indication of usability it is often sufficient to administer only a few to gain a reliable understanding of usability perceptions. One such questionnaire is the usability scale (developed by Van der Laan, Heino, & De Waard, 1997), which has routinely been employed to assess driver perceptions of telematic and DSS systems. This measure requires drivers to rate their perceptions on a number of bipolar adjective scales that are then summed to produce separate scores for the level of perceived satisfaction and usefulness. The scores can be positive or negative to reflect satisfaction/dissatisfaction and usefulness/non-usefulness.

The degree of trust drivers attribute to a particular CIIWT is a critical component of overall usability due to the notion that drivers attributing low degrees of trust to a particular system are likely to disengage or not utilize the beneficial information provided to avoid a collision, a situation which defeats the purpose of the system. Drivers can be provided with a trust metric which assesses their understanding and perceived reliability of the CIIWT system (Lee & Moray, 1992). This is a nine-point scale that rates the degree of agreement with a series of statements regarding system functioning. The scale can be aggregated to produce an average trust score and a number of additional subcomponents indicative of trust.

Conclusions

This chapter provided a review of the role of driving simulators in research examining the utility of CIIWT within land-based transportation environments. CIIWT are a subclass of driver support systems that provide in-vehicle collision warnings to drivers so they can respond appropriately to avoid collision-likely events by making informed decisions. An identification of CIIWT characteristics consisting of system actions, temporal activation, geospatial activation, hardware and software components, system integration with a vehicle or infrastructure, and the physical mechanism to deliver collision warnings helps to illuminate the complexity of these systems and the range of potential difficulties that one may be faced with when incorporating them into driving simulators for research purposes. The complexity of CIIWT technology evaluations increases still further when one considers the range of potential dependent variables within performance, workload, and usability constructs and the driving scenarios that should be paired with specific types of CIIWT technologies in order to conduct examinations that allow for a high degree of generalization of driving environment simulation results to real-world situations. The potential complexity of these evaluations should not dissuade scientific endeavors that seek a better understanding of the utility of these systems. Instead, it is hoped that the complexity of these evaluations will intrigue scientists and challenge them to conduct exceptional research which will highlight the veridical potential of these devices to improve transportation safety.

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Glossary Terms

Adaptive Cruise Control (ACC): Vehicle-based system that maintains a criterion speed and, when following a vehicle that is traveling slower than the criterion speed, will maintain a predetermined time headway.

Anti-Lock Brake System (ABS): A vehicle-based system that prevents the wheels from locking/skidding.

Collision and Intersection Incursion Warning Technology (CIIWT): Technology within the vehicle and/or within the transportation infrastructure that can provide warnings from either within or outside a vehicle to a driver of an impending collision or dangerous incursion into an intersection.

Cooperative Intersection Collision Avoidance System - Stop Sign Assist (CICAS-SSA): Intersection-based technology that can provide gap information to a driver on a minor roadway (who is attempting to cross over a major roadway) relative to traffic on a major roadway.

Driver Support System (DSS): A general term referring to a class of products that intend to support driver intentions, increase driver safety, or increase driver comfort.

Forward Collision Warning System (FCW): A radar or laser-based in-vehicle system that warns a driver if a lead vehicle is within a predetermined time headway.

Lane Departure Warning (LDW): An in-vehicle system that warns a driver if their vehicle begins to move out of lane.

Key Readings

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Web Resources

The *Handbook* web site contains supplemental material for the chapter, including color versions of two figures.

Web Figure 1: Plan view of an instrumented rural expressway intersection (color version of Figure 40.1).

Web Figure 2: Two CICAS-SSA variable message signs presenting gap and warning information to a driver positioned at a stop sign (color version of Figure 40.2).

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