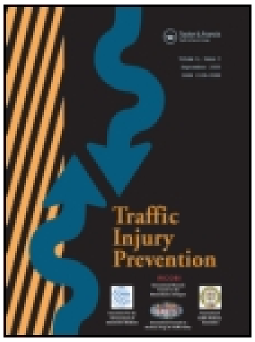

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Creating Pedestrian Crash Scenarios in a Driving Simulator Environment

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Objective: In 2012 in the United States, pedestrian injuries accounted for 3.3% of all traffic injuries but, disproportionately, pedestrian fatalities accounted for roughly 14% of traffic-related deaths (NHTSA 2014). In many other countries, pedestrians make up more than 50% of those injured and killed in crashes. This research project examined driver response to crash-imminent situations involving pedestrians in a high-fidelity, full-motion driving simulator. This article presents a scenario development method and discusses experimental design and control issues in conducting pedestrian crash research in a simulation environment. Driving simulators offer a safe environment in which to test driver response and offer the advantage of having virtual pedestrian models that move realistically, unlike test track studies, which by nature must use pedestrian dummies on some moving track.

Methods: An analysis of pedestrian crash trajectories, speeds, roadside features, and pedestrian behavior was used to create 18 unique crash scenarios representative of the most frequent and most costly crash types. For the study reported here, we only considered scenarios where the car is traveling straight because these represent the majority of fatalities. We manipulated driver expectation of a pedestrian both by presenting intersection and mid-block crossing as well as by using features in the scene to direct the driver's visual attention toward or away from the crossing pedestrian. Three visual environments for the scenarios were used to provide a variety of roadside environments and speed: a 20–30 mph residential area, a 55 mph rural undivided highway, and a 40 mph urban area.

Results: Many variables of crash situations were considered in selecting and developing the scenarios, including vehicle and pedestrian movements; roadway and roadside features; environmental conditions; and characteristics of the pedestrian, driver, and vehicle. The driving simulator scenarios were subjected to iterative testing to adjust time to arrival triggers for the pedestrian actions. This article discusses the rationale behind creating the simulator scenarios and some of the procedural considerations for conducting this type of research.

Conclusions: Crash analyses can be used to construct test scenarios for driver behavior evaluations using driving simulators. By considering trajectories, roadway, and environmental conditions of real-world crashes, representative virtual scenarios can serve as safe test beds for advanced driver assistance systems. The results of such research can be used to inform pedestrian crash avoidance/mitigation systems by identifying driver error, driver response time, and driver response choice (i.e., steering vs. braking).

Keywords: driving simulation, pedestrian crash avoidance and mitigation systems, pedestrian crash patterns, test methods

Introduction

Pedestrian Injury Crash Patterns

The risk of pedestrian injury and fatality varies around the world and is dependent on the rate of use of different transportation modes and culture. A recent analysis of crashes in the United States from 2005 to 2009 showed that crashes involving pedestrians accounted for 1.1% of all crashes but 12% of all fatalities (Yanagisawa et al. 2014). This disparity points to the vulnerability of pedestrians in the roadway environment and the relatively low speeds at which an injury becomes a fatality. Worldwide, over 400,000 pedestrians are killed in vehicle crashes annually (Naci et al. 2009). Crash causation varies across developed and developing countries (Zegeer and Bushell 2012) but, overall, pedestrians are more at risk in urban rather than rural areas. One study showed that 70% of crashes occur in an urban environment (Clifton et al. 2009).

Largely, pedestrian injuries occur at intersections or junctions with 2 lanes of travel and speed limits 25 mph or under (Jermakian and Zuby 2011). Du et al. (2013) analyzed trends and characteristics of pedestrian crashes in the United States from the 2000–2011 General Estimating System (GES) and Fatal Accident Reporting System data, along with nearly 19,000 h of video data from an ongoing naturalistic driving study, of which over 1,600 potential pedestrian conflict

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scenarios were identified and factors coded. They found that the first and second most common locations of a pedestrian in an injury crash are in marked and unmarked crosswalks, respectively. Additional modeling efforts based on the naturalistic data set included road condition and pedestrian behavior as additional factors (Tian et al. 2014). A number of studies show a large number of pedestrian-involved injury crashes occurring on the roadway but not in a crosswalk. For instance, a case study from Atlanta found that 37% of pedestrian crashes occurred when the pedestrian was jaywalking (Dai 2012).

Though roadway and traffic factors are clear contributors to crashes, the contribution of pedestrian actions should also be considered. An analysis of 2000–2009 GES data shows that the majority of pedestrian crashes involve the pedestrian exhibiting no specific action that contributed to the crash. However, jaywalking and darting/running into the intersection combined account for 43% of pedestrian injury crashes (Jermakian and Zuby 2011). Nearly 96% of pedestrian injury crashes involve a single pedestrian (Jacobsen 2003).

Vehicle safety initiatives to reduce pedestrian injuries include forgiving bumper design and pedestrian detection systems coupled with warning systems or automated braking (Crandall et al. 2002). These pedestrian collision avoidance/mitigation (PCAM) systems offer a technological intervention strategy for reducing pedestrian injuries (Jermakian 2011). Recently, the NHTSA completed a benefits estimate analysis for PCAM systems by evaluating crash types, severity, and the ability of PCAM technology to reduce injury severity (Yanagisawa et al. 2014). Their analysis showed that the highest number of crashes occurred at intersections but the rate of injury in those crashes was lower than at other locations due to the lower speeds at intersections. They also show that 80–93% of pedestrian fatalities occur outside of a marked crosswalk. In part they attribute this to drivers not expecting to see a pedestrian in these locations, thus delaying the driver's response. The scenario where the vehicle is going straight and the pedestrian is crossing the road accounts for 64% of fatalities and the vast majority of economic and societal cost.

Studies of drivers' natural reactions in crash-imminent situations involving pedestrians are needed to inform PCAM system warning timing and staging to avoid false alarms and provide the proper rate of automatic braking. The current approach uses the same analysis of crash patterns used to develop PCAM system hardware test scenarios to develop a driving simulator scenario to evaluate driver responses to PCAM systems in terms of warning timing, warning modality, and other driver assist features such as automated braking or vision enhancement systems that highlight pedestrians in the scene (Brown et al. 2010).

Use of Driving Simulation

The current study observed driver behavior across a number of pedestrian crash-imminent scenarios in the National Advanced Driving Simulator at the University of Iowa. Driving simulation provides the opportunity to put pedestrians and drivers in situations that would be extremely hazardous on the road or on a closed-course test track. The modeling of human movement in virtual environments has improved greatly, due in large part to the popularity of computer games and computer-based training. This project used 3-dimensional pedestrian models and movements from a commercially available software package used by the gaming industry (DI-Guy 2012).

Tests of driver response are typically conducted on a test track with a pedestrian dummy. This practice goes back to as early as 1968 (Barrett), and current efforts to standardize test equipment and procedures for PCAM systems are ongoing (Carpenter et al. 2013). Although these tests are necessary to evaluate the reliability of the system hardware, they have limitations when evaluating driver response. The human perceptual system is fine-tuned to detect motion, particularly in peripheral vision (Owens et al. 1994). For this reason, virtual pedestrians in a simulator with a 360° projection system provide a more realistic, yet safe, test environment.

Simulation offers the advantage of a high degree of control over the placement and timing of scenarios. Likewise, it supports the measurement of driver response in terms of eye gaze, steering, throttle, and braking at a high-frequency data collection rate. Other research teams are using simulation methods to derive PCAM system test scenarios based on crash data (e.g., Gholamjafari et al. 2014; Tian et al. 2014), but these approaches do not consider driver behavior variables such as brake reaction time and force. The data collected in studies like the one described here can be used to evaluate how PCAM systems might augment natural human responses. Data from the current study are being used by the research team to validate a computational model of driver perception and reaction in these scenarios. This article presents the rationale behind creating the simulator scenarios and some of the procedural considerations for conducting this type of research.

Method

Using Crash Patterns to Develop Driving Simulation Scenarios

The creation of a prototypical crash scenario based on crash data has been used to evaluate causal chains in injury prevention research (Fleury and Brenac 2001; Najm and Smith 2002). Many factors of a crash scenario could be manipulated and/or controlled in a simulator study and the research team examined crash patterns and previous taxonomies of crash types to prioritize the variables. Table 1 presents the variables considered in decision making about scenario design and control.

For the current study, the research team used analyses of pedestrian crash frequency and severity to devise 18 different crash-imminent scenarios to use in a driving simulator experiment. Sixteen of these scenarios were daytime scenes with the pedestrian crossing the roadway perpendicular to the car's travel direction. Two of the scenarios were nighttime scenes that presented pedestrians walking on the shoulder of the road in the same direction of travel as passing cars. An

Table 1. Factors considered in scenario development

Variable class	Factors to consider	Considerations
Vehicle movement	Direction of travel	Straight vs. turning; same vs. opposite direction
	Speed	Speed at contact
	Vehicle dynamics	Braking and acceleration; steering and handling
Pedestrian movement	Direction of travel	Parallel, crossing, near or far side of intersections
	Walking speed	Evasive maneuvers by pedestrians by changing speed or path
Roadway and roadside	Number of lanes	Through, turn, parking, bicycle lanes
	Crosswalk marking	Presence, type of signs and markings
	Roadway lighting	Presence, type, location of street lighting
	Traffic signals	Presence, type, turn and pedestrian phases
Environmental conditions	Weather	Rain, snow, fog affects visibility and pavement friction
	Time of day	Sun angle glare, darkness, dusk
Pedestrian characteristics	Age	Age affects judgment of gap acceptance, walking speed
	Gender	Males have higher involvement in pedestrian crashes
	Impairment	Large proportion of pedestrians impaired by alcohol or drugs
	Visibility Factors	Pedestrians in dark clothing more likely to be struck
Vehicle and driver characteristics	Age of driver	Drivers <25 years old have higher involvement in pedestrian crashes
	Vehicle type	Vehicle class, age, mechanical condition, presence of ADAS systems

ADAS = Advanced Driver Assistance Systems

additional goal of the study was to manipulate driver expectation of the presence of pedestrians to assess its influence on driver response time. We accomplished this by providing (or not providing) roadway cues to pedestrian activity such as advance crosswalk warning signs, crosswalk roadway markings, intersections, sidewalks, and other pedestrian activity in the vicinity. The gaze manipulation variable also served to prompt expectation of pedestrians or to distract drivers from areas of pedestrian activity.

The goal of the study was to collect driver response data in a range of pedestrian conflict situations.

Crossing Type

Crash data show that most pedestrian injuries occur at intersections, which is an indication of exposure and conflict opportunity. The more unexpected conflict areas found at mid-block locations would likely show the most benefit for PCAM systems, because the driver has a lower expectation of encountering a pedestrian mid-block. For purposes of experimental balance, statistical power, and route planning in the study, half of the pedestrian events occurred at intersections and the other half occurred mid-block. Within each of those locations some crosswalks were marked with standard U.S. parallel line pavement markings, some contained continental (zebra) markings, and others were unmarked. Marking type has been shown to affect crosswalk visibility distance (Fitzpatrick et al. 2011).

Side of the Road

In order to reduce predictability of pedestrian behavior, half of the pedestrians crossed from the driver's left and half crossed from the right. Varying the side of approach also provided natural variation in the angular size of the pedestrian at critical stopping sight distances. The driver perception portion of the larger driver modeling project relied on angular size and rate of change, so gathering driver response data across a range of target angles was important.

Expected Gaze Direction

For each event, gaze direction was manipulated by including a distracter object on either the same or opposite side of the road as the pedestrian. The distracter object was expected to attract the driver's gaze prior to the initiation of an event. We tried to manipulate driver eye gaze by placing other animated and static objects in the scene along the approach to a pedestrian event. These objects included clusters of other pedestrians walking or talking, emergency vehicles, stopped vehicles, and animals. For the purposes of the computational modeling (reported elsewhere), we were interested in driver gaze patterns. But in a more general sense, we feel that providing rich, active driving scenes increases driver engagement and immersion in the simulation.

Pedestrian Walking Speed

Walking speed was set at 1.21 m/s (2.97 ft/s; 2.71 mph) and running speed was 1.86 m/s (6.1 ft/s; 7.07 mph). These values were drawn from observations at marked and unmarked crosswalks (Brewer et al. 2006) and are slightly faster paces than those used to set traffic signal pedestrian phase timing. We erred toward a faster moving pedestrian because we felt that it represented a more challenging response scenario by reducing the time to collision. For the study, half of the pedestrians were walking and half were running.

General Considerations for Scenarios and Procedures

For the overall scenario, several design goals were made based on previous experience with driving simulator studies. We wanted the overall drive duration to be 45–60 min because past studies have shown that drivers become slightly fatigued and inattentive past that point. We wanted the drive to be continuous, not a series of short event-filled segments interrupted by simulator starts and stops. A continuous drive increases immersion and promotes natural driving behavior. Our scenarios were designed to appear as natural and plausible as possible. The first step in the scenario design was to lay out the trajectories of each of the desired 18 events in our experimental design. In order to reduce overall programming time, an existing visual database consisting of residential, rural, and urban sections was used. A route through these areas was developed that provided proper event spacing and inclusion of each of the target events. A 5- to 10-min warm-up drive with no events, hard stops, and minimal turns was included to allow drivers to be accustomed to vehicle handling and visual environments as well as give the researchers an opportunity to observe symptoms of simulator sickness. Given these constraints, the number of events per drive could be determined at one every 2–3 min. At the relatively slow driving speeds in this study and rich visual environment, pilot testing showed that this event spacing was sufficient to allow periods of uneventful driving.

One concern we had when developing the study was the effects of repeated crash-imminent events within a single experimental session. These effects could result in drivers anticipating crash events and driving more cautiously. We tried to minimize these effects by including many distracter events where it appeared that a pedestrian or vehicle would pose a threat but ultimately did not. Throughout the drive, there were many pedestrians walking on sidewalks and waiting on corners and roadsides that never entered the road. Though the overall number of potential hazards indeed likely prompted drivers to scan more thoroughly and drive cautiously, we feel that the distracters disguised the test trials. The number of collisions observed shows that at least for some drivers the events remained surprising. Ten distractor events were interspersed throughout the drive. These distractors were designed to imitate event conditions in which an event did not materialize, thereby making the actual events less predictable. For instance, one distractor included a group of children on the sidewalk in front of a school where a pedestrian did not cross the street. Two of these distractor events included bicycles on the right side of the roadway. Two more included lead vehicle sudden braking events. Though our drivers remained alert for hazards throughout the study, postdrive interviews revealed that they did not feel like they were driving an "obstacle course."

Based on conversations with other researchers in the domain, we had concerns that striking a pedestrian may cause emotional distress to our drivers. Other research centers had reported anecdotally that this was especially true for child pedestrian targets. For this reason, we included only adult pedestrians in the study. Furthermore, we did not visually model or display the physics of any collisions with a pedestrian or provide any auditory cues in the event of a collision. We were also careful in our debriefing of our participants to stress that we had placed them in unavoidable crash situations so that they would not feel bad about hitting or coming close to hitting a pedestrian. We did not have any participant express emotional distress after having been in a crash. We included a debriefing session and information sheet where we stressed that these scenarios had been developed to make crash avoidance very difficult. This debriefing also requested that the participant not discuss the study scenarios with friends or family to avoid biasing any other potential subjects.

One critical factor in scenario design is hazard preview time or distance. Our simulation software allows us to specify time to arrival as a trigger such that when the driver reaches a threshold time (based on instantaneous speed) from a location an event can be triggered. For this study, the target location was a theoretical point in the center of the lane where the vehicle and pedestrian would collide if each stayed on a straight path at constant speed. The time to arrival at this point varies

Fig. 1. National Advanced Driving Simulator (NADS-1) at the University of Iowa: (a) exterior bay and (b) dome interior view.

based on the roadway geometry of each pedestrian event location and ranged from 3.5 to 11 s. This does not mean that the pedestrian was necessarily visible that entire time. In some scenarios the pedestrian object is hidden behind buildings but must be triggered to begin moving in order to become visible at a shorter time to collision. Extensive pilot testing was required to adjust these timings for each event location with the goal of having the pedestrian target visible for 3–5 s before the theoretical collision point. One further complication in simulating pedestrian movement is that the walking speed is not constant. Because the DI-Guy (2012) pedestrian models' movements are based on actual human motion capture, there is a slight startup time before the pedestrian reaches the target walking speed. Again, pilot testing was needed to adjust for this. In some cases, the walking/running speed of the pedestrian had to be adjusted in addition to its starting location.

One other design decision we made was to keep the path and speed of the pedestrian constant (after initial startup). Though our software supports trigger-based changes in path and speed, these were controlled to simplify the experimental design. Observational studies of pedestrians (e.g., Brewer et al. 2006) have shown the pedestrians often stumble, drop things, retreat, or start running in the course of street crossing.

Fig. 2. Single forward visual channel near view of mid-block pedestrian entering road.

Future studies should consider these negotiated movements as pedestrians change their behavior when a vehicle approaches.

Apparatus

The National Advanced Driving Simulator (NADS-1) at the University of Iowa was used for data collection. A Chevy Malibu sedan vehicle cab is mounted within a dome with a 360° horizontal and 40° vertical field of view imaging system that consisted of 16 light-emitting diode projectors. Each projector has a vertical resolution of 1,920 pixels and horizontal 1,200 pixels, resulting in a minimum 1.1 visual arc resolution per pixel. The dome and vehicle move within 13 degrees of freedom in a motion envelope that can produce lateral and longitudinal acceleration forces of up to 0.6 g (see Fig. 1).

Ultimately, the driving scenario consisted of a continuous route through urban, residential, and rural environments in dry daytime conditions. Two nighttime conditions were presented along the 55 mph rural section to enable the testing of the pedestrian-on-shoulder events with the lighting changing instantaneously from day to night. These changes were accompanied by an automated voice prompt indicating that sometimes the scene may change to nighttime. The drive typically took 35–40 min. To reduce order effects, participants completed the route in one of 2 reversed orders counterbalanced across age and gender groups. Auditory prompts alerted the driver to upcoming turns and auditory speed warnings were triggered if the driver exceeded ± 5 mph of the posted speed limit, which was 55 mph in the rural section, 40 mph in the urban section, and alternated between 20 and 30 mph in the residential section, respectively. A front video channel image from the simulator for an example scenario is shown in Fig. 2. Figure 3 shows a plan view of the scenario used in experiment planning. Additional images of the simulator visual scenes and diagrams for all 18 scenarios are available in the online supplement.

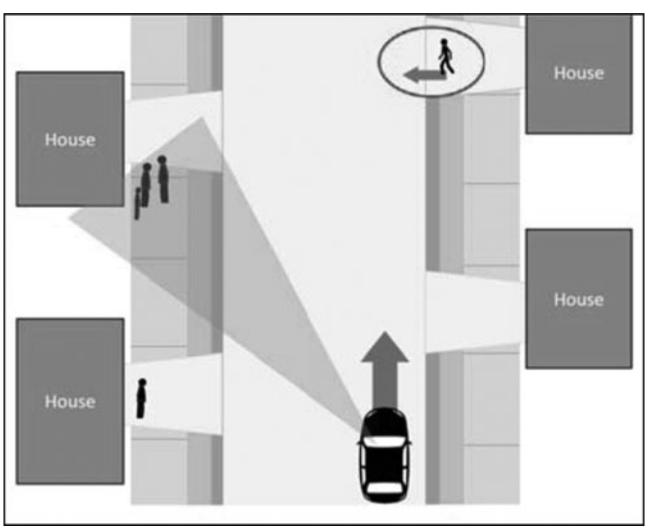

Fig. 3. Plan view of pedestrian event illustrated in other figures. Shaded area represents intended driver gaze direction.

Results

The first of 3 studies using these scenarios was completed with 48 subjects run. Anecdotal feedback from these drivers indicates that the inclusion of distracter events did succeed in disguising the true study focus on pedestrians. Most participants reported that they were driving more defensively than normal due to all the "crazy drivers" in the scenarios.

Driver braking and steering are the main variables of interest. A joint distribution of brake response time and force will be examined to understand the relationship between these 2 measures. Past research has shown that late response often result in higher brake force and increased attempts to steer to avoid a collision (Mazzae et al. 1999). The research team plans further analyses of the data to further dissect the response patterns looking at throttle release times and eye-scanning patterns. Analysis of eye-tracking data will also allow us to assess the success of our manipulation of driver gaze direction. The results of this study will inform a computational model of driver response that can be used to evaluate advanced driver assistance systems such as forward collision and pedestrian detection and warning systems. By understanding the range of drivers' responses under a wide variety of roadway environments and crash trajectories, warning timing and automatic braking algorithms can be developed and evaluated.

Discussion

One challenge of driving simulation research is simulator sickness. The sickness rate for the NADS-1 simulator is usually less than 5% of participants, a low rate, which we attribute to prescreening subjects for motion sickness propensity, the high fidelity of the motion system, and minimizing the number of sudden stops and tight turns in scenario. For the current study, residential and urban areas were used to match the crash data. These environments naturally resulted in 19 individual 90° turns at intersections and frequent stopping and starting. Due to this our sickness rate rose to 20%. Future studies should carefully consider the number and spacing of events and attempt to create a test route minimizing turns and stops.

Based on crash patterns, the next major category of pedestrian injury crashes is conflicts between turning vehicles and pedestrians. Turning scenarios present some unique challenges in simulation in terms of sightline obstruction due to vehicle A-pillars. Given the relatively high rate of simulator sickness in the first study, there are concerns over the head turning and horizontal visual search required for pedestrians while the driver is turning a corner. Pilot studies will be required to adjust the turn radius, visual complexity of the surrounding scene, and event spacing to mitigate the likelihood for sickness.

Future research examining driver response to other vulnerable road users, such as bicyclists, is also desirable. Again, simulation offers a safe environment in which to test this. The DI-Guy (2012) software includes moving bicycles with programmable path and speed. Distracted pedestrians and bicyclists is another area of interest for our research team (see Nasar et al. 2008) and some new machine-vision based pedestrian detection systems may be able to identify distracted pedestrians and issue appropriate warnings to the driver or pedestrian.

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Supplemental Materials

Supplemental data for this article can be accessed on publisher's website

References

Barrett GV. Feasibility of studying driver reaction to sudden pedestrian emergencies in an automobile simulator. *Hum Factors.* 1968;10:19–26.

Brewer M, Carlson P, Fitzpatrick K, Turner S, Ullman B. *Improving Pedestrian Safety at Unsignalized Crossings*. Washington, DC: Transportation Research Board; 2006. Transit Cooperative Research Project Report 112.

Brown TL, He Y, Roe C, Schnell T. Is more better?—night vision enhancement system's pedestrian warning modes and older drivers. *Ann Adv Automot Med.* 2010;54:343–350.

Carpenter MG, Feldmann M, Moury MT, et al. *Objective Tests for Forward-Looking Pedestrian Crash Avoidance/Mitigation Systems*. Washington, DC: NHTSA, US Department of Transportation; 2013. DOT HS 811 793.

Clifton KJ, Burnier CV, Akar G. Severity of injury resulting from pedestrian–vehicle crashes: what can we learn from examining the built environment. *Transp Res D Transp Environ.* 2009;14:425–436.

Crandall JR, Bhalla KS, Madeley NJ. Designing road vehicles for pedestrian protection. *BMJ.* 2002;324:1145–1148.

Dai D. Identifying clusters and risk factors of injuries in pedestrian–vehicle crashes in a GIS environment. *J Transp Geogr.* 2012;24:206–214.

DI-Guy™ Software. Cambridge, MA: VT MAK Corporation; 2012.

Du EY, Yang K, Jiang F, et al. Pedestrian behavior analysis using 110-Car Naturalistic Driving data in USA. Paper presented at: 23rd International Technical Conference on the Enhanced Safety of Vehicles; May 27–30, Seoul, Republic of Korea; 2013.

Fitzpatrick K, Iragavarapu V, Chrysler ST, Park ES. Detection distances to crosswalk markings: transverse, continental and bar pairs. *Transp Res Rec.* 2011;2250:1–10.

Fleury D, Brenac T. Accident prototypical scenarios, a tool for road safety research and diagnostic studies. *Accid Anal Prev.* 2001;33:267–276.

Gholamjafari A, Li L, Chien S, Chen Y. Genetic algorithm-based testing scenarios selection for the performance evaluation of crash imminent braking systems for pedestrian safety. Paper presented at: IEEE Intelligent Transportation Systems Conference; October 2014.

Jacobsen PL. Safety in numbers: more walkers and bicyclists, safer walking and bicycling. *Inj Prev.* 2003;9:205–209.

Jermakian JS. Crash avoidance potential of four passenger vehicle technologies. *Accid Anal Prev.* 2011;43:732–740.

Jermakian JS, Zuby DS. *Primary Pedestrian Crash Scenarios: Factors Relevant to the Design of Pedestrian Detection Systems*. Charlotesville, VA: Insurance Institute for Highway Safety; 2011.

Mazzae EN, Baldwin GS, McGehee DV. Driver crash avoidance behavior with ABS in an intersection incursion scenario on the Iowa driving simulator. Paper presented at the Society of Automotive Engineers Annual Meeting; 1999.

Naci H, Chisholm D, Baker TD. Distribution of road traffic deaths by road user group: a global comparison. *Inj Prev.* 2009;15:55–59.

Najm W, Smith J. Breakdown of light vehicle crashes by pre-crash scenarios as a basis for countermeasure development. In: *Proceedings of the International Conference on Applications of Advanced Technologies in Transportation Engineering*. 2002:712–719.

Nasar J, Hecht P, Wener R. Mobile telephones, distracted attention, and pedestrian safety. *Accid Anal Prev.* 2008;40:69–75.

NHTSA. *Traffic Safety Facts 2012 Pedestrians*. Washington, DC: Author; 2014. DOT HS 811 888.

Owens DA, Antonoff RJ, Francis EL. Biological motion and nighttime pedestrian conspicuity? *Hum Factors.* 1994;36:718–732.

Tian R, Li L, Yang K, Chien S, Chen Y, Sherony R. Estimation of the vehicle–pedestrian encounter/conflict risk on the road based on TASI 110-Car Naturalistic Driving data collection. Paper presented at: IEEE Intelligent Vehicles Symposium; June 2014.

Yanagisawa M, Swanson E, Najm WG. *Target Crashes and Safety Benefits Estimation Methodology for Pedestrian Crash Avoidance/Mitigation Systems*. Washington, DC: NHTSA, US Department of Transportation; 2014. DOT-VNTSC-NHTSA-13-02.

Zegeer CV, Bushell M. Pedestrian crash trends and potential countermeasures from around the world. *Accid Anal Prev.* 2012;44:3–11.