Augmented Reality for Safer Pedestrian-Vehicle Interactions

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UNIVERSITY TRANSPORTATION CENTER

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A Report on Research Sponsored by

SAFER-SIM University Transportation Center

Federal Grant No: 69A3551747131

September 2018

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Abstract

Communicating the presence of pedestrians or bicyclists to vehicle drivers can lead to safer interactions with these vulnerable road users. Advanced knowledge about the presence of these users on the roadway is particularly important when their presence is not expected or when these users are out of range of the advanced safety systems that are becoming a standard feature in vehicles today. For example, having advanced knowledge of a pedestrian walking along a rural roadway is key to increasing driver awareness through in-vehicle warning messages that provide an augmented version of the roadway ahead. As connected vehicles start to enter the market, it is conceivable that when the vehicle sensors detect a pedestrian on a rural roadway, the pedestrian presence can be communicated to vehicles upstream of the pedestrian location that have not reached the destination. As part of the research presented, an experiment was conducted in which the detection of pedestrians by subjects was tested with and without an advanced warning about the pedestrian presence ahead. For comparison purposes, in addition to testing the detection of pedestrians as a result of advanced warning messages on rural roadways, the same situation was tested on urban roadways.

1 Introduction

Pedestrians are among the most vulnerable users of the transportation system. Augmented reality (AR) has the potential to improve the safety of vehicle and pedestrian interactions. Augmented reality is often treated as a science fiction tool capable of overlaying information on the existing world by using glasses or futuristic lenses. However, different levels of AR exist, and an augmented reality version of a roadway can be as simple as a vehicle communicating to the driver that there is a potentially unsafe situation ahead prior to the driver realizing that danger on their own. For example, if a vehicle is capable of communicating the presence of an unexpected pedestrian or bicyclist that is not yet visible to the user, that AR version of the roadway could be a lifesaver, especially since the low visibility of pedestrians is often the cause of vehicle-pedestrian accidents along with other factors such as alcohol, drowsiness, speeding, or distraction [1].

If drivers receive help from their vehicles in detecting pedestrians, pedestrian injuries and fatalities could be reduced. The technology for pedestrian detection is already available, and various algorithms have been developed and successfully tested for recognizing pedestrians. These algorithms work with in-vehicle infrastructure as well as with roadside infrastructure such as vehicle- and pedestrian-detection systems. The challenge continues to be how to communicate the output of these algorithms to the drivers. As connected vehicle technology grows, it is conceivable that, when a connected vehicle detects a pedestrian on the road, the presence of that pedestrian can be communicated to other connected vehicles. If the presence of a pedestrian is unexpected, such as on a low-volume rural highway, an in-vehicle warning system can be used to provide an AR version of the roadway ahead to drivers to increase attention and improve pedestrian detection prior to the point at which a collision-avoidance system needs to be triggered.

1.1 Objectives

The objective of the research described in this report is to determine if an advanced warning message (in the form of auditory and visual cues) can have an impact on the detection of pedestrians/bicyclists if the warning is triggered a significant distance ahead of the pedestrian/bicyclist. The objectives of the research were achieved by:

- creating an experiment in a driving simulator that exposes drivers to situations in which pedestrians are not expected, and
- collecting data about pedestrian recognition based on input from the participants of the experiment.

1.2 IRB Approval

The experimental and data collection procedures described in this report were conducted after receiving approval from the University of Wisconsin-Madison (UW-Madison) Social Sciences institutional review board (IRB). The public data sharing procedures described in the report were also approved by the aforementioned IRB and included in the consent documents signed by the experiment participants. All members of the research team involved in the project received the required training involving the use of human subjects in experiments and were listed in the research protocols submitted and approved by the UW-Madison Social Sciences IRB. The protocol number assigned to this experiment by the UW-Madison Social Sciences IRB was 2018-0710.

2 Literature Review

In recent decades, humans have relied on the automobile as the primary mode of transportation. Driving has become ubiquitous and is almost second nature to most adults. However, the reality is that driving is a complex task that requires processing large amounts of roadway and environmental information under tight time and pressure constraints. These constraints force drivers to prioritize information and to only process a small percentage of visual auditory information at once. Most of the time, drivers are able to handle the complexities of the driving process without mishaps. However, when drivers fail to react appropriately to a situation, or fail to recognize a dangerous scenario, the consequences of such an event can range from a simple near-miss to a roadway fatality. Scenarios that involve a pedestrian fatality caused by drivers are often among those where the failure to recognize a dangerous situation is exemplified.

Recent advances in technology are often tied to increased distraction [2, 3] and have been found to be the cause of pedestrian-related fatalities [4]; however, these advances can also make promising technologies available to drivers that can be used to improve the safety of our transportation system. One such technology is AR, which could be used to provide drivers with key information about the roadway conditions ahead. Augmented reality has the ability to improve safety by providing drivers with advanced warning information. In particular, AR has the potential to improve the safety of vehicle and pedestrian interactions. Existing literature relevant to the areas of drivers, pedestrians, AR technology, and in-vehicle technology will be discussed in this section.

2.1 Driver Behavior

Drivers are prone to making mistakes because of inherent human physical, perceptual, and cognitive limitations. In fact, driver error has been identified to be the main cause in 75 to 95% of roadway crashes [5, 6]. Human error has been the subject of research for a long time, leading to several taxonomies that explain the theory behind errors and provide a unique analysis perspective. However, three perspectives dominate: Norman's [7] error categorization, Reason's [8] slips, lapses, mistakes, and violations classification, and Rasmussen's [9] skill, rule, and knowledge error classification [6]. These three perspectives categorize major driving errors into errors of recognition, errors of decision, and errors of performance. Perception and interpretation can be identified as recognition. Situations that can lead to recognition errors include inattention, distraction, and looked-but-failed-to-see errors. Planning and intention can be identified as decision. Decision errors include misjudgment, false assumption, improper maneuver, excessive speed, inadequate signaling, and driving too close to other vehicles. Action execution can be identified as performance. Performance errors include overcompensation, panic, freezing, and inadequate directional control [10].

Stanton and Salmon [6] applied the three taxonomies on the impact that human error had on drivers while interacting with intelligent transportation systems (ITS) such as automated cruise control, navigation systems, and collision warning systems. They were able to identify 24 potential driver errors, and they assigned a potential ITS solution that might reduce or eliminate error occurrence. These driver errors are human errors in driving, which are classified into four categories: slips, lapses, mistakes, and violations, according to Reason [8]. Slips are actions not carried out as planned, whereas lapses are missed actions attributed to memory failure. Slips and lapses occur at the execution level. Mistakes arise from deficiencies in the judgmental process and occur at the planning level. Violations occur when drivers don't conform to rules and regulations and can be grouped into unintended or deliberate deviations. Exceeding the posted speed limit if the driver missed the traffic sign would be an example of an unintended violation, whereas knowingly speeding would be an example of a deliberate violation [11].

Driver attention is a key component of driving. A decade ago, distracted driving involved the use of a cellphone (calling or texting) while driving. Since then, advancement in technology has led to more distracted drivers and increased crashes. Concerns about distraction have gained national attention [12, 13]. Eysenck [14] defines attention as the ability of an individual to focus on certain objects and allocate processing resources accordingly. Distraction is lack of attention and is defined as anything that takes away the attention allocated to a primary task. Previous studies have shown that distraction accounts for a big portion of road traffic crashes [15, 16]. When encountering some level of internal or external distraction, drivers could take their attention away from the roadway and decrease their situational awareness and the ability to perceive and comprehend environmental elements [16].

2.2 Augmented Reality Technology

Augmented reality differs from virtual environments (VE), or virtual reality as it is more commonly called. With VE technologies, users are completely immersed in a synthetic environment and cannot see the real world around them. In contrast, AR allows the users to see the real world with additional virtual objects overlaid on the real world. Hence, rather than completely replacing reality, AR supplements it; virtual and real objects appear to coexist in the same space. The most commonly accepted definition of AR states that it is any system that has the following three characteristics:

1. It combines real and virtual;
2. It is interactive in real time; and,
3. It is registered in three dimensions [17].

Augmented reality is an example of intelligence amplification in which a computer is used as a tool to make a task easier for a human to perform by providing additional information about the environment. It can provide drivers with a variety of information in a discrete manner and can be as simple as an additional piece of information or as complex as a complete environment makeover. Augmented reality relieves the burden on drivers by projecting what they see with informative details. It also improves the user’s perception and interaction with the real world. Information that the user cannot easily or directly detect with his or her own senses are indicated or emphasized by the virtual objects. This information helps the user better perform the real-world tasks [17].

With enhancements in computer graphics and the increase in processing power of computers, AR technology has achieved a significant jump. It has permeated several areas, such as medical visualization and training, manufacturing and assembling, maintenance and construction, design and modeling, military training and warfare, commercial applications, various forms of entertainment, navigation, and information guidance. One of the most computationally intensive challenges that all AR applications have in common is the requirement to precisely align virtual images with objects in the real world [18].

Two main techniques exist for combining real and virtual objects: an optical technique and a video technique. The optical technique combines real and virtual objects by using an optical combiner. The video technique combines the video of the real world with virtual images by using a computer or a video mixer. Due to the high cost associated with the optical AR technique, the possible delay between the real-world view and the superimposed virtual images, and the problem of matching the brightness of real and virtual objects using this technique, the video AR technique is more appropriate for many applications. Both techniques can display the final view to the user using a head-mounted display (HMD), a monitor-based display, and/or a hand-held display [18].

Augmented reality can also add visual aspects as simple as an LED to the real world to augment information about the environment. LEDs have a high resistance to vibrations and light up very quickly [19]. They can transmit messages that the human eye cannot see [20].

Many researchers have focused on the benefits of AR in navigation, but it can also improve the capabilities of safety systems by augmenting and assisting critical secondary tasks. For instance, AR can augment active safety systems designed to help prevent a vehicle accident. These systems include blind zone alerts, forward collision warning, adaptive cruise control (ACC), following distance indication, rear cross traffic alert, blind zone alert, lane change warning, and lane drift warning. Augmented reality cues can also assist older drivers with visual cognitive impairments in situations associated with high risk potential, such as left-turn cases [21].

2.3 In-Vehicle Technologies

The market for in-vehicle systems has grown in past years. Researchers and manufacturers have tested several in-vehicle display systems for both research and commercial applications. The most common types of in-vehicle displays are head-down display (HDD), HUD, and AR display [22-32].

Head-down displays refer to displays positioned in the middle of the vehicle's control panel. Although HDD is helpful in navigation, drivers must take their eyes off the road in order to read this display while driving. Hence, they pose a potentially serious problem when it comes to driver distraction [24].

Head-up displays project the required information directly into the driver's line of sight, i.e., the windshield. Thus, drivers receive information without taking their eyes off the road [24]. Continental, one of leading manufacturers of HUD, is supplying vehicles such as BMW, Mercedes Benz, and Audi with HUD [33]. So far, HUD has been used to convey speedometer data, navigation directions, roadway speed limits, and warnings at the specific section of the road the driver is going through [22, 26, 28].

Liu and Wen [24] investigated the effects of HDD and HUD on the driving performance psychological workload ratings in commercial vehicles. Participants were asked to perform four different tasks: commercial goods delivery, navigation, detecting and maintaining speed, and response to an urgent event. In terms of average accuracy rate for the first task, commercial goods delivery, drivers performed similarly when using HDD or HUD. As for the response time to an urgent event, drivers reacted faster and the speed control was more consistent with HUD than with HDD in both the low and high workload cases. Drivers also showed less mental stress with HUD when the workload was low than they did with HDD.

Augmented reality display is the most advanced technology currently on the market and is being tested in luxury car brands. An AR display is a more advanced form of HUD that can convey lane departure warnings, automated cruise control and blind spot monitoring augmented on the road itself. For instance, if the driver is deviating away from the lane, the vehicle will produce visual, audible, and haptic alerts to warn the driver about the situation he is facing. Augmented reality can also enable, for example, a virtual arrow to be augmented and displayed upon the road itself for better navigation. Another example includes illuminating the roadway at night [33].

2.4 Testing In-Vehicle Technologies

As the market for in-vehicle technology continues to grow, there have been several studies that involved in-vehicle technology. In-vehicle technology includes Bluetooth to voice command systems and information display systems. Although in-vehicle systems are useful in one or more ways, avoiding distraction and attention deficits while driving is a challenge in in-vehicle systems. Bach et al. [32] looked at 100 papers and classified them into two categories: evaluation of settings for in-vehicle systems and measure of driver attention relevant to in-vehicle systems. The classification showed that most studies were conducted in driving simulators and real traffic driving. Lateral and longitudinal control and eye behavior were the most-used measures for driver attention. The studies also showed that in-vehicle systems interaction can increase safety while driving if minimal or no interaction induced visual demands.

The Minnesota Department of Transportation (MnDOT) conducted a study [27] to examine if driver compliance with speed limits increased when supplemental information from in-vehicle systems was present. Results from the study showed that drivers prepared to adopt the new speed limits before entering a zone and in most cases complied with the zone speed limits, regardless of whether or not the in-vehicle systems information was there. The study also evaluated driver performance in a driving simulator to examine if distractions occurred while using in-vehicle systems. The results indicated that in-vehicle systems information reduced the workload for drivers. In-vehicle systems were most useful in situations where drivers were unfamiliar with the route.

Using a driving simulator, Boyle and Mannering [30] evaluated driving behavior using in-vehicle and out-of-vehicle traffic advisory systems. Four different advisory-information conditions were analyzed: in-vehicle messages, out-of-vehicle messages, both types of messages, and no messages. Two weather scenarios were also considered, fog and no fog, as well as two types of incidents, snowplows and no snowplows. Study results showed no significant difference in mean speed and standard deviation speed over long segments. The study also found that once the information message had either passed or become out of range, drivers would speed up to compensate for the lost time incurred from being warned to slow down.

A study by Schall et al. [23] evaluated the effectiveness of AR cues in assisting cognitively impaired elderly drivers and improving their safety. Speed-of-processing, defined as the time it takes a person to perform a mental task, was used to evaluate driver behavior when AR cues directed the attention of the drivers to roadside hazards compared to when they were absent. The AR cues helped subjects detect low-visibility roadside objects like pedestrians and warning signs. They also improved response time and response rates. A similar study by Rusch et al. [25] was conducted on middle-aged drivers. Response time for detecting a potential hazard was used to evaluate drivers. Results showed that response time for detecting hazardous objects decreased as a result of AR cues. Thus, AR cues may offer promising benefits to improve driver safety.

A full-windshield HUD system was used by Wu et al. [34] to detect and highlight road signs. The system was shown to help drivers navigate more easily in complex driving situations. A study by Tonnis et al. [35] compared presenting information to drivers through AR cues and through an exocentric frame. The results showed that AR cues helped drivers in situations where they had to divide their attention between several tasks in the car. In another study, Tonnis et al. [36] developed two visual representation schemes – a braking bar assistance scheme and a drive-path assistance scheme – in the HUD of cars. The study showed that the visual cues did not increase the overall workload for drivers. Drivers had a better feeling of safety using the assistance cues.

Kim and Dey [37] proposed an AR windshield-based in-vehicle navigation system to help drivers reduce issues related to divided attention between paying attention to road while driving and looking at the navigation system. Drivers who used the proposed navigation system had fewer navigation errors and divided-attention-related issues than drivers not using that system. The results also showed that AR cues can help minimize the cognitive workload of older drivers.

Test subjects participated in a study by Cheng et al. [22] that instrumented a test vehicle with different forms of HUD: a warning sign, a numeric warning showing the driver's speed along with the speed limit, and a graphical representation of the vehicle speed and speed limit. Speed data along with other vehicle parameters were recorded as participants drove on actual roads. Results showed that the most effective presentation of HUD information was a simple warning sign that consisted of a triangular exclamation point sign. This display was presented only when the driver exceeded the speed limit. The display pattern was identified as a bouncing effect where the location of the sign changes vertically, similar to a rubber ball on cement.

Another study by Rusch et al. [38] assessed the effects of AR cues on middle-aged and older drivers to help them make a left turn across oncoming traffic. The study showed that the time to make a left turn was shorter when AR cues were available than when they were not. Response rate for drivers with and without impairment increased with AR cueing, and older drivers' performance was similar to middle-aged drivers with AR cues. The study also showed that AR cues did not distract the driver; they focused the driver's attention on the road.

A recent study [39] investigated a new AR traffic sign recognition system in improving driving safety. The results showed that during the decision-making phase, AR cues impact the allocation of visual attention. The study also showed that the proposed system can detect signs in sunny and rainy weather, and at day and night.

Tran et al. [40] proposed a left-turn aid with an AR-HUD to allow drivers to make a safe left-turn decision. The system projects a 3 second path of the oncoming vehicle, allowing the driver to determine whether or not it is safe to make a left turn. The results showed that the more aggressive drivers tended to accept higher gaps, whereas the more conservative drivers accepted smaller gaps than they normally did. Augmented reality cues helped drivers know when it was safe to turn.

2.5 <u>Pedestrian-Vehicle Interaction</u>

Pedestrians are some of the most vulnerable users of the transportation system, especially when crossing a roadway [7]. Drivers prefer traveling at stable, maximum speeds with minimum delays and stops, whereas pedestrians are reluctant to wait at curbs for long times or to change their walking speeds/paths. When pedestrians and drivers intersect, a pedestrian-vehicle conflict situation is created. Tunnels or bridges, signalized crosswalks, or marked uncontrolled crossings (zebras) are measures to eliminate such conflict and reduce pedestrian accidents. On an uncontrolled crossing, the pedestrian has to step into the road when it is safe to do so, both for him and the approaching driver. Katz et al. studied driver-pedestrian interaction during the crossing conflict. The results showed that drivers slowed down or stopped for crossing pedestrians in 5 cases: the driving speed was low, pedestrians crossed on a marked crosswalk, the distance between the vehicle and the pedestrian was long, a group of pedestrians crossed the road, and the pedestrian crossed without looking at vehicular traffic. The results also showed that female drivers and older drivers slowed down more than other drivers [1].

Pedestrians are hit twice as often by vehicles making left turns than by vehicles making right turns. That is, the risk of a vehicle-pedestrian accident is significantly higher in situations where pedestrians share green time with vehicles turning left than where they share green time with vehicles turning right. Poor driving habits and visibility of pedestrians from within the vehicle were the factors responsible for the difference between left- and right-turn accidents [41].

Yang et al. [42] studied the behavior of pedestrians and their interaction with vehicles. The study looked at pedestrian-vehicle interaction videos and studied which scenarios might be most dangerous and result in potential conflicts. The results showed that pedestrians identified as children alone are at the highest risk of pedestrian-vehicle accidents. Potential conflicts occur more at parking lots, communities, school areas, shopping malls than in regular urban/rural driving environments. Potential conflicts also occur more at crosswalks and junction than at other road types.

2.6 Augment Reality Cues for Pedestrian Detection

Advanced driver-assistance systems (ADAS) have been developed to enhance driving safety and driving experience. These assistance systems have been highly successful in reducing the severity and the number of driving accidents. A type of ADAS, the pedestrian collision warning system (PCWS), is used to detect the presence of pedestrians and warn the driver about potential dangers. The PCWS consists of three stages: detecting the pedestrian (finding its position); obtaining the motion vector of the pedestrian; and predicting its future path, calculating collision time, and determining the possibility of collision [43]. Pedestrian collision warning systems are currently able to detect the presence of pedestrians with high accuracy. In the case of possible collisions, the PCWS alerts the driver through beeps and sounds [44].

Phan et al. [44] designed a new PCWS with AR cues and assessed the driver's awareness of a pedestrian using a driving simulator. Visual AR cues were used as they can help in conjunction with auditory cues. The proposed system highlights pedestrian presence with a conformal bounding box, and in the case of a potential collision, it alerts the driver. The study showed that AR cues helped the driver achieve a higher perception level; the driver noticed the box that highlighted a pedestrian before noticing the pedestrian. The driver was more vigilant with AR cues; the cues gave the driver a sensation that a pedestrian might cross the road, which made the driver slow down in some situations. When the cues were displayed, the driver applied less pressure on the accelerator pedal and anticipated a pedestrian crossing; the driver did not brake as urgently as without cues.

Navigation system users focus on the system itself rather than focusing on the path, creating distraction problems. As pedestrians benefit from such systems, Chung et al. [45] proposed a mindful walking navigation system for pedestrians. More context information was provided through the use of an AR interface, allowing pedestrians to pay more attention to the path rather than the map and the environment. Pedestrians were also offered the chance to choose their path, which increased the perception of control. Both conditions were found to increase pedestrians' navigation performance and environment exploration. Augmented reality displays reduced visual attention division between the environment and the device. The study suggested that the use of AR cues can reduce cognitive load and minimize divided attention.

2.7 Literature Review Summary

Through an extensive literature review, it was shown that advanced in-vehicle technologies offer great potential in presenting information to drivers at the needed time. This information includes navigation, logistics, and safety measures. The AR display is currently the most advanced technology on the market. One variation, AR-HUD, is displayed on the windshield – in the driver's line of sight – and help direct the driver's attention to the road. These displays also help improve drivers' response time to hazards; AR-HUD regulatory and warning traffic signs were found to have an impact on drivers' speed compliance similar to that of post-mounted signs. The literature review also looked at the behavior of drivers and pedestrians. Pedestrian-vehicle interaction conflicts are most common on marked uncontrolled crossings. However, there remains a hole in the research when it comes to evaluating the AR displays related to pedestrians. Combining all the many distractors and theories for human error provides an avenue to keep exploring the idea of using advanced in-vehicle systems to provide a safer interaction between vehicles and pedestrians.

3 Scenario and Experimental Procedures

Experimental procedures described in this report were conducted on a full-scale driving simulator located at UW-Madison, shown in Figure 3.1. Characteristics of the driving simulator are presented in the sections ahead. Subjects recruited for the experiment drove a virtual world in the simulator, and data produced by the simulator was used to analyze driving behavior. The virtual work designed for this experiment exposed subjects to driving conditions designed to achieve the previously defined objectives of the project. The characteristics of the virtual world to which the subjects were exposed are discussed in the following sections, as is the consent process that subjects went through prior to participating in the experiment.

Figure 3.1 – Full-scale driving simulator at UW-Madison

3.1 UW-Madison Driving Simulator

As previously noted, the UW-Madison full-scale simulator shown in Figure 3.1 can display a virtual world in which experiment participants (subjects) interact with the roadway environment as if they were on a real highway and driving a real car. As part of the typical operation of the driving simulator, data about the vehicle state is collected at a rate of 60 Hz. Data collected includes, but is not limited to, speed, position, lane position, steering angle, brake pedal position, and gas pedal position. In addition to vehicle state data, the driving simulator can also log responses from the user for specific situations by logging the timestamp associated with the push of the steering wheel buttons. However, for the experiment described in this report, the research team relied on a separate instrumentation approach to collect responses from users that involved the use of a push button. The supplemental instrumentation used is described in section 4.4.

3.2 Subject Consent Process

Before participating in the experiment, subjects were first shown the driving simulator and provided an overview of how the system operates. After the introduction to the system, subjects were asked to read and sign a consent form if they decided to continue with the experiment. After the consent, subjects drove a practice session on the simulator, and finally proceeded to participate in the experiment. At multiple times during the introduction to the system, subjects were reminded that they could stop the simulation with an emergency push button and that they could withdraw from the experiment at any time. Additional details about the consent process and the practice sessions are provided in the following sections. Details about the subjects recruited for the experiment are described in section 4.2. All subjects had a valid driver's license.

3.2.1 Consent Process

A written informed consent was used as a guide to explain the study. It involved giving subjects adequate information about the study, responding to any questions they asked, and ensuring that subjects understood the information conveyed. A signed copy of the consent form was kept by the research team, and subjects were given a copy of the consent form containing contact information in case they had questions about the study.

3.2.2 Practice Session after Consent

Subjects practiced driving the simulator for 5 minutes before the experimental drive. The practice drive took place in an urban environment in normal weather conditions and with good visibility. Subjects were asked to make maneuvers such as navigating curves and turns and changing lanes, and they were told to drive as they normally would in their own vehicles.

3.3 Scenario for Experiment

The scenario for the experiment described in this report was created by considering the objectives of the experiment as well as the limitations of simulation experiments that typically make it infeasible to keep drivers in a simulation environment for extended periods of time. The sections ahead describe the specific goals of the scenario, as well as other characteristics, such as the geometry of the roadway alignment that defines the scenario.

3.3.1 Experimental Goals

The primary goal of the experiment was to determine if advanced warning about the presence of a vulnerable road user (e.g., a pedestrian) communicated to drivers via an in-vehicle warning system had an impact on the detection of these road users by drivers. The warning system used to communicate the presence of vulnerable road user ahead was a combination of visual and auditory cues that were triggered during the experiment based on a pre-defined experimental matrix.

The full-scale driving simulator experiment involved situations in which subjects were asked to detect the presence of pedestrians/bicyclists. The detection task was evaluated in a variety of workload environments. Workload environments in which the subjects were asked to complete the detection task included: driving through a rural freeway cross section while following a car, navigating through sharp curves on a rural highway, and navigating through a typical urban environment.

3.3.2 Geometric Characteristics

The scenario involved rural cross sections followed by urban cross sections. Driving was conducted with the simulator set to emulate normal weather conditions (day driving, good visibility, no rain or snow). The rural portion of the drive was 3,660 meters (2.3 miles) long, and the urban portion was 3,380 meters (2.1 miles) long. Figure 3.2 shows the three typical rural cross sections in the experiment (in the order experienced by the subjects), and Figure 3.3 shows the continuous urban cross section.

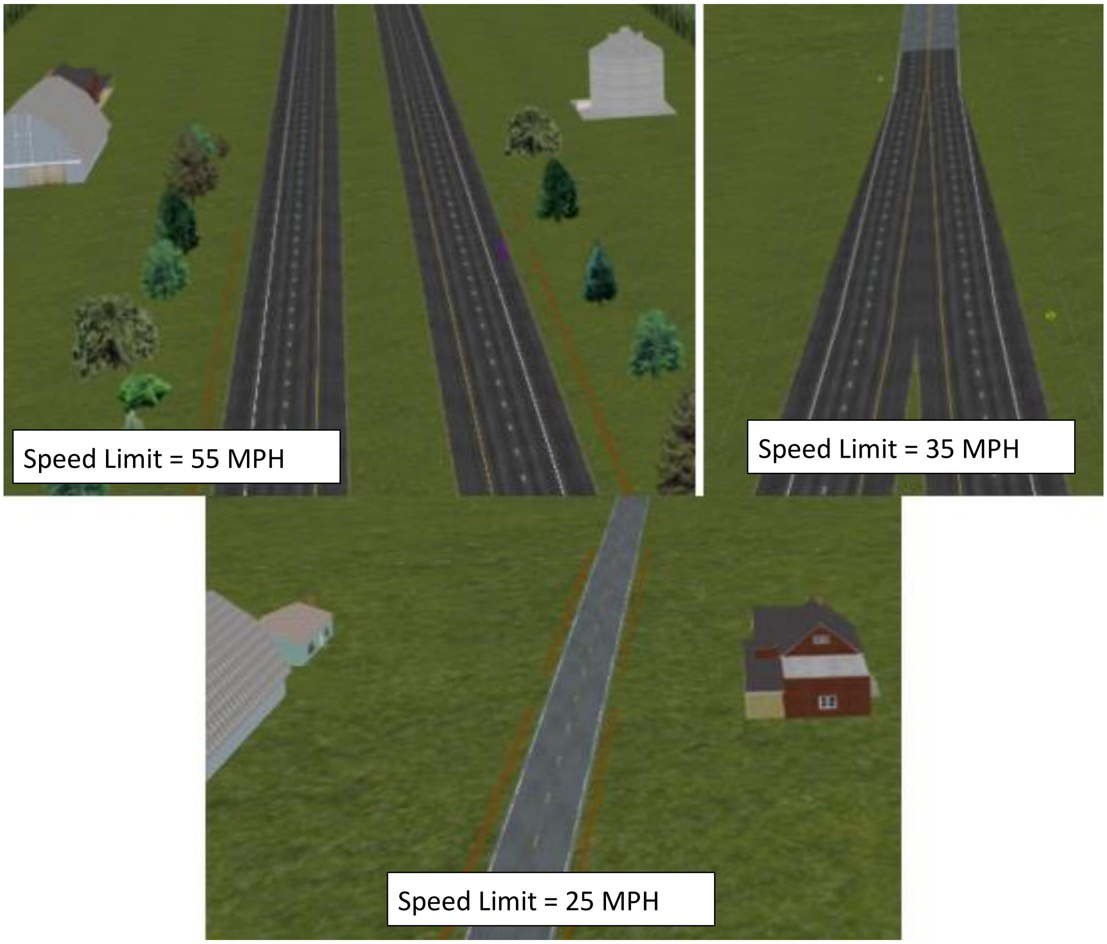

Figure 3.2 – Typical rural roadways cross sections in experiment

Figure 3.3 – Urban roadways cross section

3.3.3 Navigation Guidance

In the rural portion of the scenario, subjects were asked to follow a lead vehicle that then exited the roadway prior to reaching key test areas. Following the lead vehicle was used as a secondary task in the rural environment given the expected low workload subjects would experience in such an environment. In the urban section of the roadway, light traffic was added to meet the expectations of an urban environment.

In the urban environment, signs at signalized intersections were used to provide guidance to drivers regarding the turns to make. These guidance signs are shown in Figure 3.4. Additionally, in both the rural and urban environments, regulatory signs such as posted speed limit and warning signs such as horizontal alignment signs (W1-5), chevron alignment signs (W1-8), and divided highway sign (W6-1), were also used.

Figure 3.4 – Custom guide sign messages

4 Experimental Design and Data Collection Procedures

4.1 Experiment Tasks

As previously mentioned, the experiment involved subjects driving through a rural portion of the virtual world and then through an urban portion. On the rural portion, subjects were asked to follow a leading vehicle until it moved to the side of the road. On the urban portion, subjects were asked to follow the navigation instructions previously shown in Figure 3.4. For the duration of the experiment, subjects were asked to press the buttons on a clicker once they saw a pedestrian or a bicyclist. In total, subjects had to click 7 times for events that included a bicyclist or a pedestrian. The 7 events were presented in the following order: bicyclist driving on rural shoulder (1 event), bicyclist driving on road (1 event), pedestrian hitchhiking (1 event), and pedestrians crossing the road (4 events). Additional details about each event are presented in Table 4.1 - .

Table 4.1 - List of bicyclist and pedestrian events

Event number	Event description
Event 1	Bicyclist on rural freeway shoulder
Event 2	Bicyclist on a 15 mph street
Event 3	Pedestrian hitchhiking after winding road
Event 4	Pedestrians crossing on a straight street
Event 5	Pedestrians crossing after a curve
Event 6	Pedestrians crossing after a curve
Event 7	Pedestrians crossing after a curve

4.2 Subject Characteristics

The initial experimental plan used to develop the experimental matrix discussed in Section 4.3 was based on 20 subjects. However, as will be discussed later, 21 subjects were recruited for the experiment. Subjects recruited were an average of 30 years old (ranging from 21 to 70 years of age), with 15 males and 6 females. All subjects were licensed drivers with driving experience between 6 and 52 years. All had normal to corrected-to-normal vision.

4.3 Experimental Matrix

Numerous versions of the same scenario were created to accommodate the requirements of an experimental matrix designed to randomize the cues (or lack of cues) to which subjects were exposed. Cues about the presence of pedestrians/bicyclists were communicated to subjects using an in-vehicle message and auditory signals. Figure 4.1 shows the dashboard icon displayed as part of the visual cue. Each visual cue was accompanied by a simultaneous auditory cue in the form of a beep.

Figure 4.1 – No alert displayed (left) versus alert displayed (right)

As a result of the experimental design and number of subjects initially planned for the experiment, 140 events were identified. In 50% of the events, subjects did not receive a visual and auditory cue about the presence of a pedestrian/bicyclist, while in the remaining 50% of the events, an auditory and visual cue was triggered. Cues were triggered as a function of time-to-arrival to an event position. The time-to-arrival was calculated based on the vehicle speed. When the calculated time-to-arrival was 20, 30, or 40 seconds (pre-defined in the scenario), cues were triggered. The experimental matrix was designed to provide a close-to-uniform distribution of these cues across events.

4.4 Subject Response Measured in the Experiment

In addition to collecting vehicle performance data that is typically obtained for driving simulation experiments, subjects were asked to press the button on a clicker when they saw a pedestrian/bicyclist. A photo of the device (a Bluetooth™ button) used to collect the response is shown in Figure 4.2.

Figure 4.2 – Push button

4.4.1 Example of Subject Response Collection (Events 2 and 3)

The pedestrian and bicyclist detection task was required for each of the 7 previously mentioned events. An example of the detection task is shown in Figure 4.3. Upon arrival to a winding road rural section, subjects were expected to detect the presence of a bicyclist, and upon exiting the winding portion of the road, subjects were expected to detect a pedestrian. The time at which the subjects pressed the push button shown in Figure 4.2 was documented and expressed as a function of the simulator time, thus allowing the data analysis presented in Chapter 5.

Each time the button was pushed by the subject, a timestamp was logged in a cellphone. Logging the timestamp was possible by using a commercially available application named Automate that is compatible with mobile devices based on the Android™ platform.

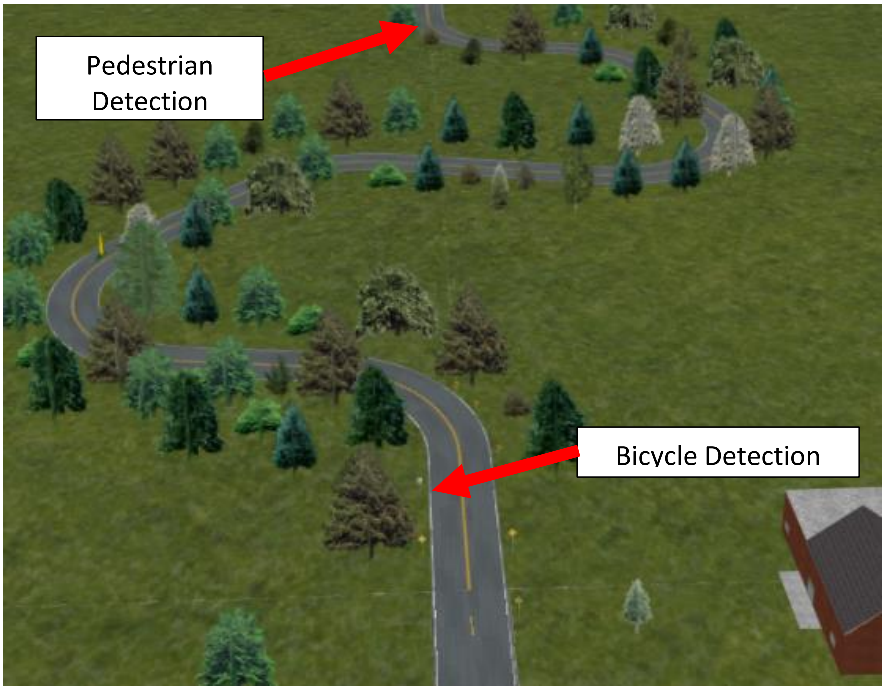

Figure 4.3 – Winding road – 15 mph

4.5 Additional Data Collected

Typical vehicle performance data (speed, position, and time) were collected as part of the experiment and used to supplement the previously mentioned response data. Additionally, video recordings of the experiment were used to simplify the data analysis process presented in Chapter 5. Neither the subject's face nor voice were recorded.

5 Data Analysis and Results

The sections ahead discuss the results of analyzing experimental data collected from the driving simulator, as well as data from the response collection system that relied on a Bluetooth push button. Results and observations were confirmed by video recordings obtained during the experiments. Throughout the analysis process, data collected were visually inspected to identify extreme values.

5.1 Summary of Data Collected

Twenty-one subjects were recruited to participate in the experiment. The oldest driver (70 years old) dropped out after the practice session due to simulation sickness concerns. Additionally, a technical malfunction prevented the completion of the experiment for another subject. As a result, experimental data is available for analysis from a total of 19 subjects. The sections ahead provide a summary of the data collected from a different analysis perspective.

5.1.1 Location of Detection Event

Each driver reacted differently to seeing a pedestrian/bicyclist. Figure 5.1 through Figure 5.7 show the location of the driver in X and Y coordinates along the road while approaching each of the 7 events.

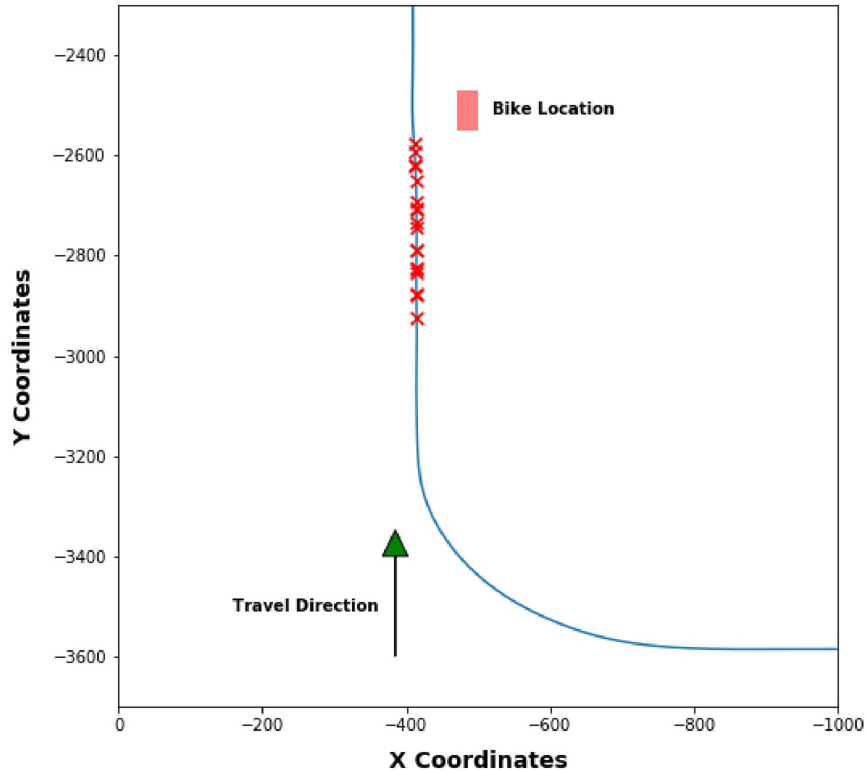

Figure 5.1 – Location of bike detection in rural environment

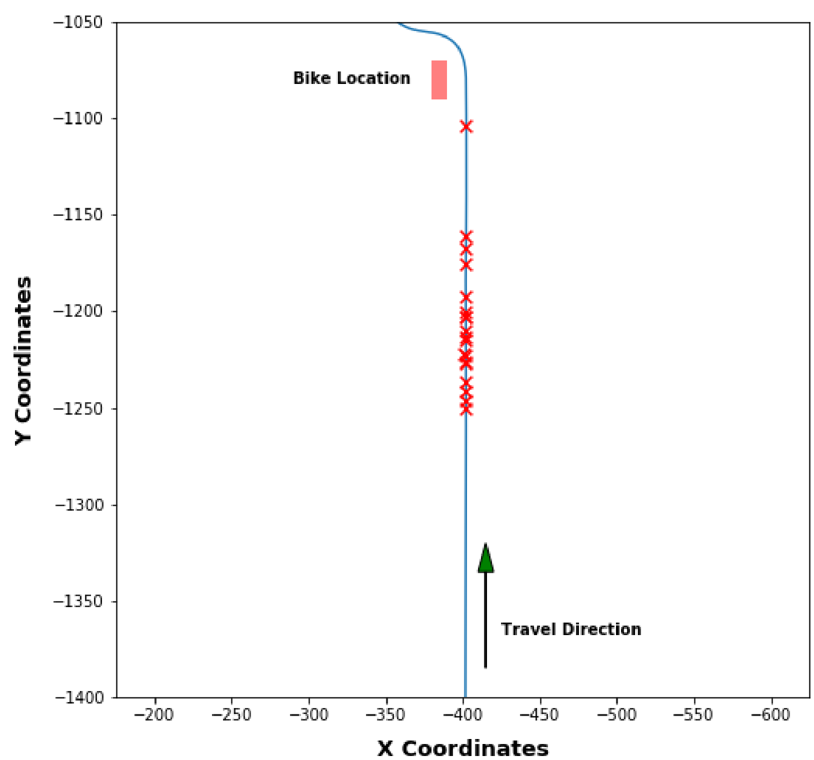

Figure 5.2 – Location of bike detection before winding road

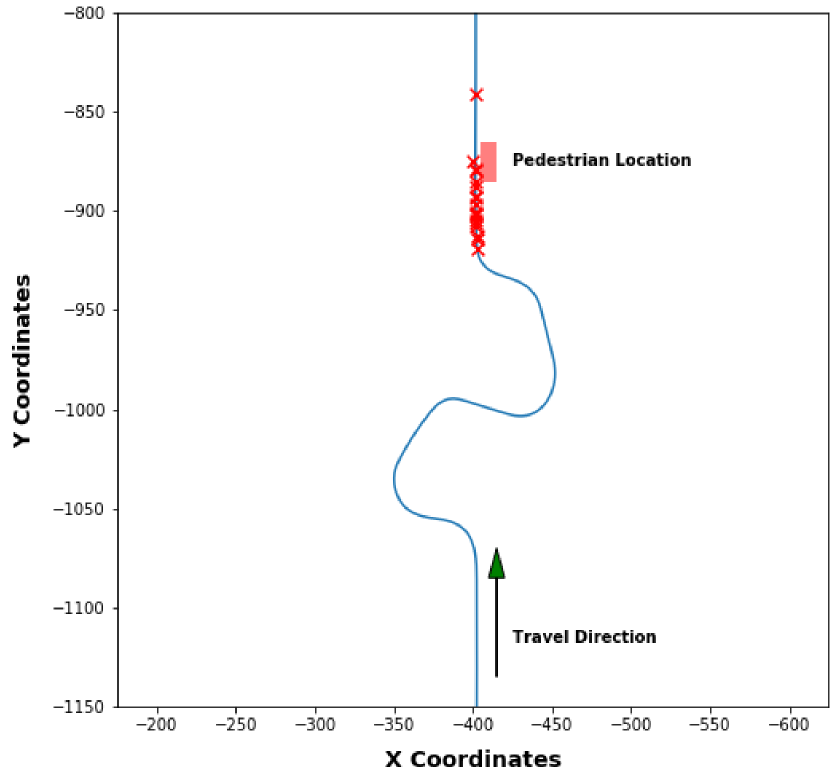

Figure 5.3 – Location of pedestrian detection after winding road

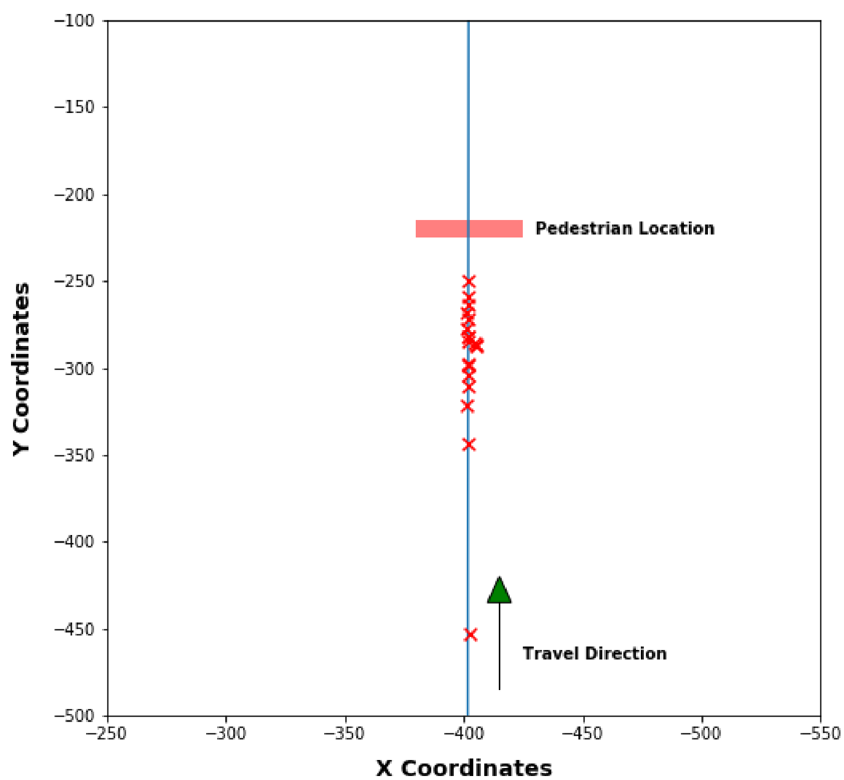

Figure 5.4 - Location of first pedestrian detection in urban environment

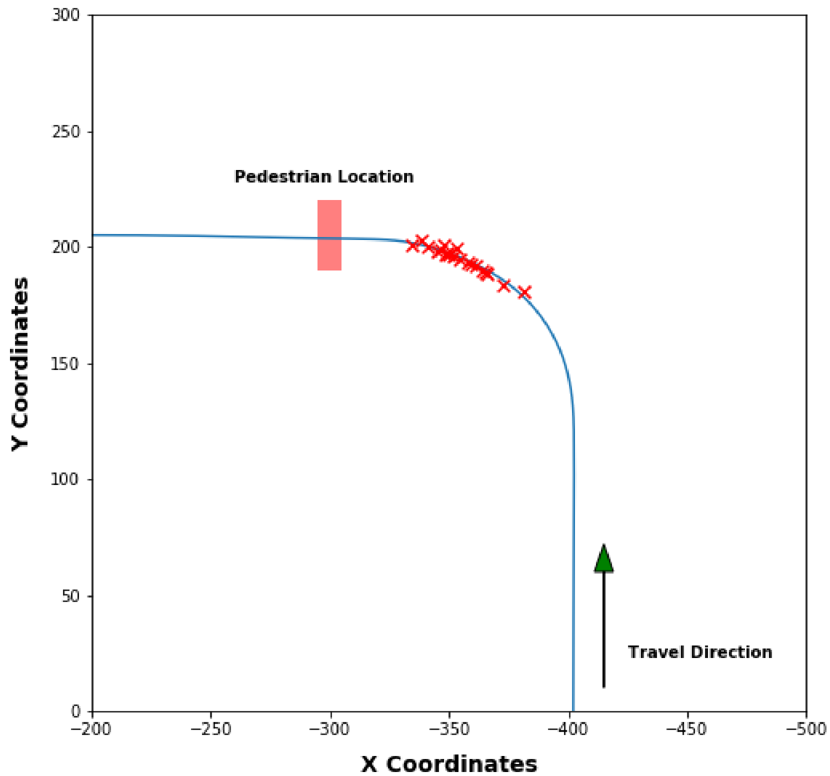

Figure 5.5 – Location of second pedestrian detection in urban environment

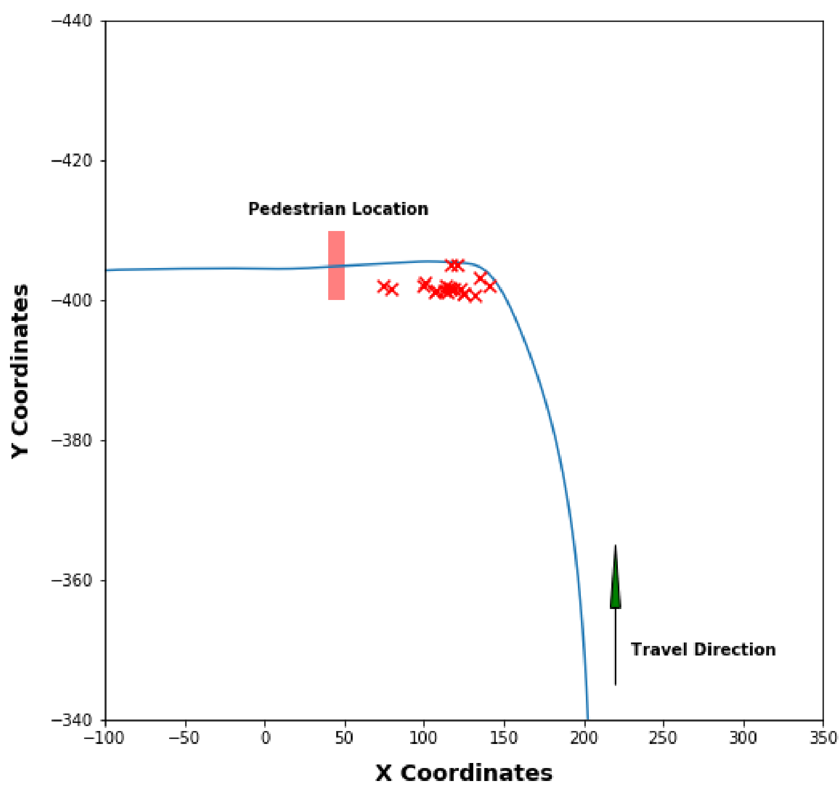

Figure 5.6 – Location of third pedestrian detection in urban environment

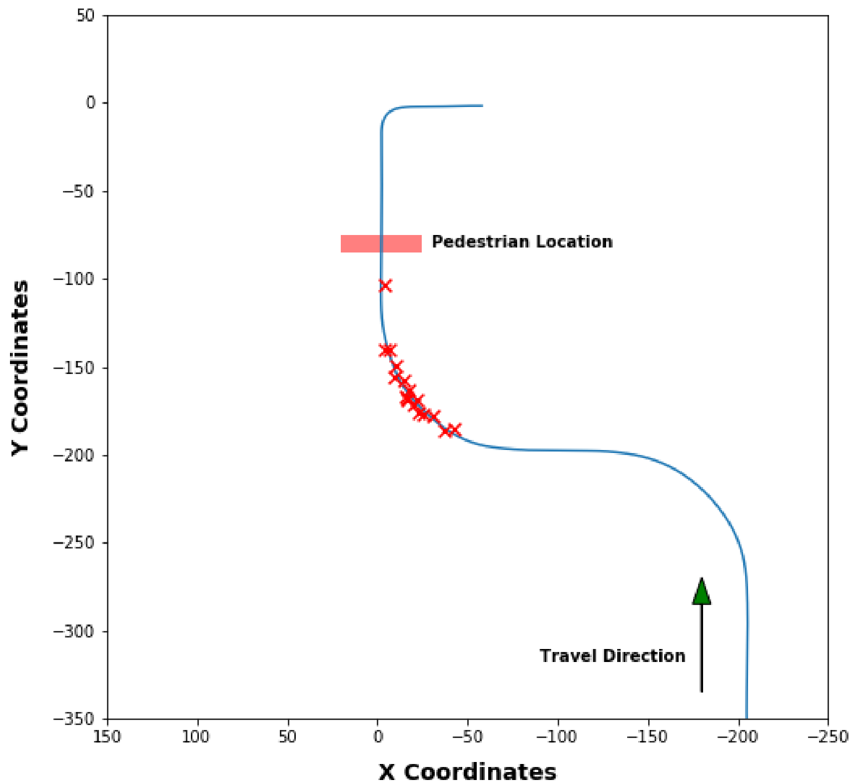

Figure 5.7 – Location of fourth pedestrian detection in urban environment

5.1.2 Additional Data Available for Each Subject

For each subject, vehicle position (Cartesian coordinates), velocity (mph and m/s), and distance traveled are available as a function of simulation time. For events that had an alert displayed, the time at which the alert was displayed is also available. The simulation time when subjects saw a bicyclist or a pedestrian is also available. All data available from the experiment were grouped into treatment and no treatment groups, and into sub-treatment groups.

5.2 Principles Used in Data Analysis

For each subject, data was visually inspected to remove missing performance measures. This is due to subjects not seeing an event, usually the first one. Several statistical filtering methods rely on the mean and standard deviation as a central trend indicator of an outlier. However, this method introduces three concerns:

- This method assumes normally distributed data (outliers included).
- The mean and the standard deviation are strongly influenced by outliers.
- This method fails to detect outliers in a small sample size.

The median, another central trend indicator, is considered a resistant estimator and is very insensitive to outliers' presence in the sample. The median absolute deviation (MAD) is defined as follows:

$$MAD = median\{|x_i - \tilde{x}|\}$$

where x_i is the individual observation and $\tilde{x}$ is the median the datasets. A MAD value is calculated for each reaction distance in the data set as the absolute difference between the reaction distance and the median of all reaction distances. The modified Z-score M_i is defined as follows:

$$M_i = \frac{0.6745\ (x_i - \tilde{x})}{MAD}$$

If the absolute value of the modified Z-score $|M_i|$ exceeds 3.5, the corresponding reaction distance is considered an outlier.

5.2.1 Statistical Tests Used

Many statistical tests, such as t-test, analysis of variance (ANOVA), and regression, require the data to follow a normal or Gaussian distribution. These types of tests are called parametric tests because their validity depends on the distribution of the data. In order to draw reliable interpretations, normality and other test assumptions should be evaluated before the use of the test. In situations where the normality assumption is violated, non-parametric tests are recommended and used instead. Hence, before starting the analysis, collected data was inspected for normality to determine the appropriate test to use by performing preliminary tests.

Normality can be checked by visual inspection from density or quantile-quantile plots (Q-Q plots). Density plots and Q-Q plots were generated for each analysis category. In addition to visual inspection, the Shapiro-Wilk test is used to compare the sample distribution to a normal one in order to ascertain whether or not the data deviates from a normal distribution.

When comparing two groups, a t-test was used if the data was normally distributed, whereas the parametric Mann-Whitney Wilcoxon test was used if the data was not. In the case of comparing more than two groups, ANOVA was used if the data was normally distributed, whereas the parametric Kruskal-Wallis test was used if the data was not.

5.3 Results of Distance-Based Analysis

The dataset was analyzed as whole set, and the control group was compared against the three different cue alerts. In addition, the control group was compared against the combination of cue alerts. Similar comparisons were conducted for each event. In addition, the data were grouped into three categories: rural, urban, and low-speed. Comparison analysis was also conducted for each category. To visualize the data, a box plot and a mean plot that summarize the data were used for each group, event, and category.

5.3.1 Distance-Base Analysis for All Data

A box plot and a mean plot are shown in Figure 5.8 and Figure 5.9 to visually summarize the data for each group. The plots are a representation of the data after filtering the outliers. The average distance reaction for events without an alert was 93.72 meters (307.5 ft), whereas the average reaction distance for events with an alert was 103.85 meters (340.7ft), 93.61 meters (307.1 ft), and 107.88 meters (353.9 ft) for treatments 1, 2, and 3, respectively.

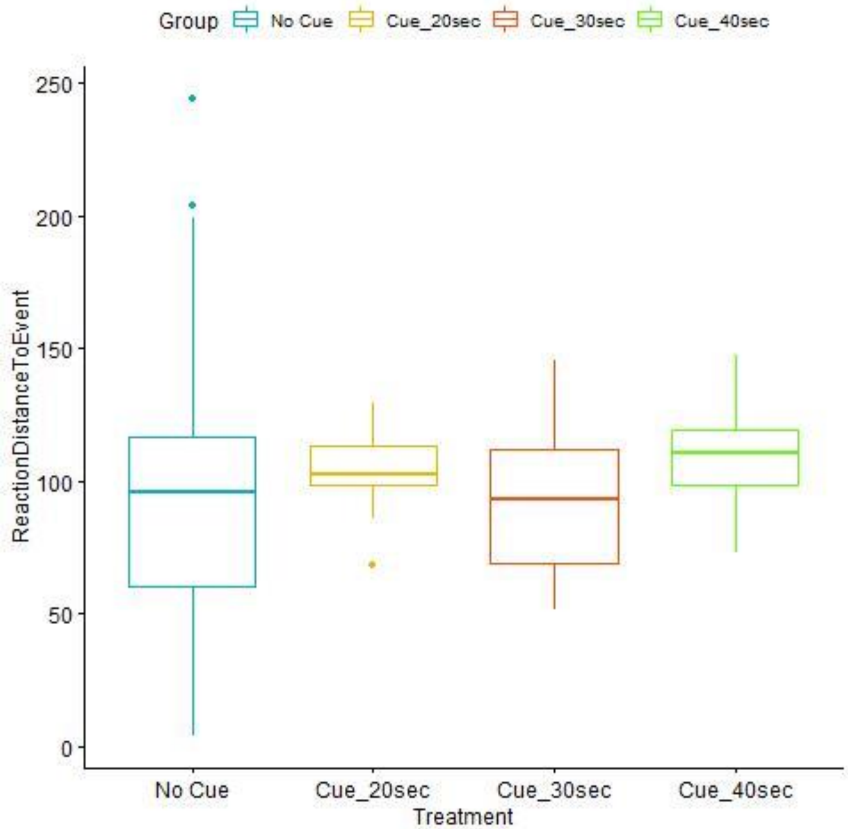

Figure 5.8 – Box plot per group

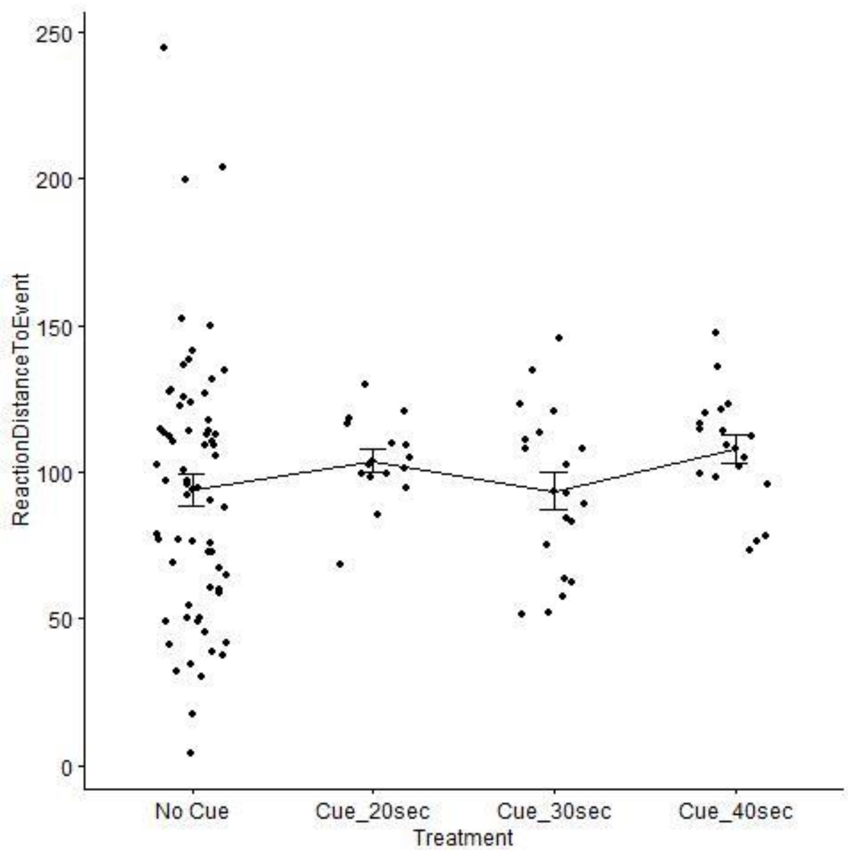

Figure 5.9 – Mean plot per group

For each group, selected summary statistics are shown in Table 5.1. These values are for the whole dataset after removing outliers.

Table 5.1 - Summary statistics for the dataset (control versus each treatment)

All data				
	No Cue	Cue1	Cue2	Cue3
Sample Size	66	15	19	18
Mean	93.72	103.85	93.61	107.88
Standard Deviation	44.51	14.94	28.27	19.57
Median	96.15	102.74	93.01	110.73
IQR	56.35	14.49	42.77	20.80
p-value – Kruskal-Wallis test	0.26			

Because there was no statistically significant difference between the mean distances of groups, all the treatments can be grouped in one group, and additional analysis can be carried out. Selected summary statistics for giving drivers an alert versus no alert are shown in Table 5.2.

Table 5.2 - Summary statistics for the dataset (control versus all treatments)

All data		
	No Cue	All Cues
Sample Size	66	52
Mean	93.72	101.50
Standard Deviation	44.51	22.58
Median	96.15	103.75
IQR	56.35	27.80
p-value – Wilcoxon Test – 1-sided	0.088	

Carrying out the analysis for the two groups (alert/no alert) using a one-sided Wilcoxon test showed a statistically significant difference between the mean distances of both groups. It should be noted that this mean difference is 7.8 m, equivalent to 25.6 ft.

5.3.2 Distance-Based Analysis by Event

After investigating the data as a whole, the same statistical procedure was carried out for each event. The Kruskal-Wallis test was used to check if there was any statistically significant difference between the distance means of any of the alert treatments and no alert. A summary of the p-value results per event is shown in Table 5.3.

Table 5.3 – Summary of Kruskal-Wallis test p-value per event

Kruskal-Wallis test – No Cue vs Cue1 vs Cue 2 vs Cu3	p-value
Event 1	0.75
Event 2	0.80
Event 3	0.10
Event 4	0.22
Event 5	0.19
Event 6	0.46
Event 7	0.87

With no statistically significant difference between the distance means of the treatments for each event, the treatments were combined into one group. The Wilcoxon test was used to check for significant difference between the distance means of alert/no alert for each event. A summary of statistics for Event 4 is shown in Table 5.4, and the p-vale summary results per event are shown in Table 5.5.

Table 5.4 – Summary of Wilcoxon test 2-sided p-value for Event 4

Event 4 – Alert for pedestrians on a straight street		
	No Cue	Cue
Sample Size	9	8
Mean	66.13	87.72
Standard Deviation	15.58	23.10
Median	72.78	83.74
IQR	22.29	24.04
p-value - Wilcoxon Test – 2-sided	0.046	

Table 5.5 – Summary of Wilcoxon test 1-sided p-value per event

Wilcoxon Test – No Cue vs Cue	p-value
Event 1	0.47
Event 2	0.50
Event 3	0.82
Event 4	0.023
Event 5	0.93
Event 6	0.73
Event 7	0.30

Event 4 (pedestrians crossing on a straight street) is the only event that showed a statistically significant difference between the distance means of the alert and no alert groups. The difference is 21.6 m, which is equivalent to 70.9 ft.

5.3.3 Distance-Based Analysis by Category

A similar analysis is carried out for each category: rural, urban, and low speed (15 mph). Kruskal-Wallis was used to compare the distance means between no alert and the three different alert treatments. The p-value result for each category is shown in Table 5.6.

Table 5.6 – Summary of Kruskal-Wallis test p-value per category

Kruskal-Wallis test – No Cue vs Cue1 vs Cue 2 vs Cu3	p-value
Rural	0.75
Urban	0.96
Slow speeds	0.64

None of the three categories showed a statistically significant difference between the distance means of no alert and any treatment alert. Therefore, all treatments were grouped into one group, and a one-sided Wilcoxon test was used to investigate whether there was a difference between the distance means of the two groups: no alert versus alert. A summary of selected statistics for the urban category is shown in Table 5.7, and a summary of the p-values per category is shown in Table 5.8.

Table 5.7 – Summary of Wilcoxon test 1-sided p-value for urban environment

Urban		
	No Cue	Cue
Sample Size	39	36
Mean	97.65	101.74
Standard Deviation	26.66	17.38
Median	102.67	103.45
IQR	36.86	22.65
p-value - Wilcoxon Test – 1-sided	0.36	

Table 5.8 – Summary of Wilcoxon test 1-sided p-value per category

Wilcoxon test – No Cue vs Cue	p-value
Rural	0.47
Urban	0.36
Slow speeds	0.21

5.3.4 Distance-Based Summary of Findings

The Kruskal-Wallis test was used to examine whether a statistical difference exists between the distance means of no alert and three different alert treatments. Analyzing the data as a whole, per event, and per category, the test results showed no statistically significant difference between the distance means of any of the groups. With no statistically significant difference between the distances mean of the treatments, the three treatments were combined into one group. The Wilcoxon test was the used to check if there was any statistical difference between the distance means of the alert and no alert groups. For the whole dataset, using a one-sided Wilcoxon test showed a statistically significant difference between the distance means of both groups with a difference in means of 7.8 m, equivalent to 25.6 ft. The test results also indicated that Event 4 (pedestrians crossing on a straight street) showed a statistically significant difference between the distance means of the alert and no alert groups. The difference is 21.6 m, equivalent to 70.9 ft. No statistically significant difference between the distance means between groups was found per category.

5.4 Speed-Based Analysis

Speed profiles were plotted for each subject. In addition to driver's speed, the moment an alert was displayed and every time the driver clicked the push button when seeing a pedestrian or bicyclist were shown on the same speed profile. An example of such a profile is shown in Figure 5.10.

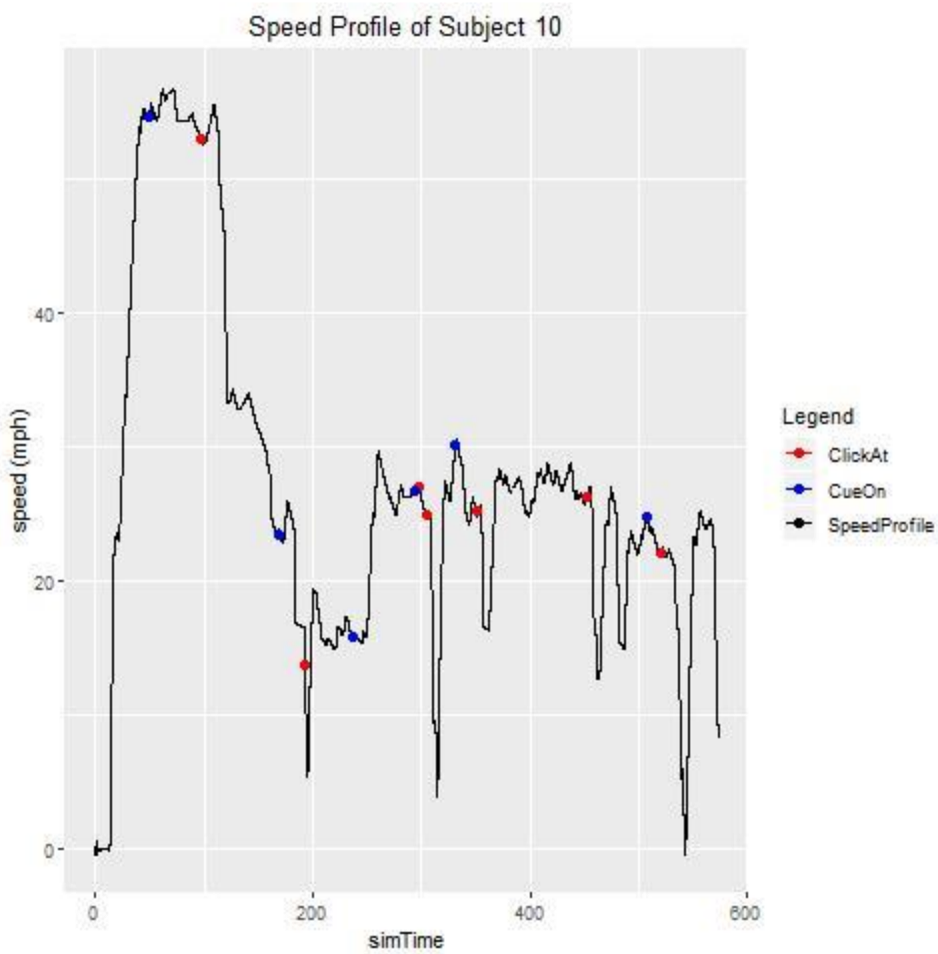

Figure 5.10 – Speed profile example (Subject 10)

5.4.1 Descriptive Statistics for Speed-Based Analysis

Looking at the speed profiles for the 19 subjects, drivers reduced their speed for 72.3% of the events after seeing an alert. Drivers decreased their speeds for an average of 14 seconds. For each alert treatment, a summary of statistics is shown in Table 5.9.

Table 5.9 – Duration of speed decrease in seconds per alert treatment

	Cue 1	Cue 2	Cue 3
Sample Size	18	12	17
Mean	12.1111	14.1667	17.1176
Minimum	3	5	4
Maximum	22	27	42
Standard Deviation	4.523	7.40802	10.2767

Drivers decreased their speeds to below the posted speed limit, giving them more time to travel. For example, although the alert was given 20 seconds prior to the event for Treatment 1, drivers slowed down for a maximum of 22 seconds before reaching the event.

On average, the speed reduction was of 4.9 mph. The values ranged between 0.5 to 21.1 mph. A high-speed reduction corresponds to subjects driving above posted speed limit. Once subjects saw/heard the warning message, a tendency to match the speed to the posted speed limit was observed.

5.4.2 Summary of Findings for Speed-Based Analysis

Speed profiles portrayed drivers' behaviors. Drivers reduced their speeds for a duration of 14 seconds on average after receiving an alert. This reduction in speed shows that once drivers are alerted to an event, they reduce their speed and pay more attention to their surroundings.

6 Conclusions

There is no question that vehicle technology has improved over time and continues to improve. Some of the most important advances in the technology have led to the inclusion of advanced/active safety systems that can help drivers avoid collisions by either initiating an avoidance maneuver or by providing a timely warning of a potential collision. As technology continues to evolve and connected vehicle technology becomes ubiquitous, it is conceivable that vehicle sensors will be able to detect the presence of pedestrians or bicyclists and communicate the presence of these vulnerable road users to other vehicles.

In a typical urban environment, where pedestrians and bicyclists are expected, such a feature is probably not as valuable as in a rural environment where there is not an expectation of finding a pedestrian or a bicycle on the side of the road. Therefore, if technology reaches a point in which an instrumented and connected vehicle detects a bicyclist or pedestrian on a rural roadway and communicates that message to other vehicles, then these vehicles could provide drivers with an advanced warning of a potentially unsafe situation caused by the presence of an unexpected/vulnerable road user.

As part of the research project described in this report, an experiment was conducted to study the impact that cues communicating the presence of a pedestrian/bicyclist ahead had on the detection of the pedestrian/bicyclist by a driver. The experiment did not focus on the detection of pedestrians that were already within the visual range of the subject but instead focused on communicating the presence of pedestrians that were not yet within the visual range of a driver. In other words, cues in the experiment were designed to provide advanced warning of pedestrians/bicyclists.

6.1 Summary of Results

The distance at which pedestrians/bicyclists were detected by the subjects was compared for groups of events associated with cues and no cues. When a cue was triggered, statistical tests suggest that subjects detected the presence of pedestrians/bicyclists 25 ft earlier than when no cues were triggered. However, this average distance was computed by grouping different speed zones. When individual speed zones were analyzed, no statistical difference was observed except for a situation in which subjects were asked to detect a pedestrian crossing the road instead of a pedestrian or bicyclist moving along the road. While no statistically significant difference was observed, one promising observation made by the research team is that variances in the location where pedestrians are detected are lower when a cue is used. Lower variances might suggest that, when a cue is triggered, behavior is more predictable; that could be attributed to subjects paying more attention to the roadway conditions. Another behavior observed by the research team is related to the speed followed by subjects. When a cue was triggered, for most events (approximately 73%) there was an average speed reduction of 4.9 mph observed. When no cues were triggered, no speed reductions were observed near the location of the events.

6.2 Future Work

An analysis of the results suggests that sample size may be one of the limiting factors of the experiment. Therefore, future work should focus on expanding the number of observations per event. Furthermore, the driving simulator itself is a limiting factor because of the complexities of the experiment. As part of future work, a lower-fidelity experiment should be conducted to assess the spatial effectiveness of cues on the attention of subjects. These lower-fidelity experiments could be conducted using dynamic surveys that expose participants to a pre-recorded driving scenario via a computer screen.

6.3 Summary of Student Involvement

Student involvement was key to the completion of the research project described in this report. Student involvement started in the planning stages of the research and continued through the preparation of the final report. During the project, students directly and indirectly involved with the project had an opportunity to learn research skills that are key to a successful career in engineering. As part of the research project, students had an opportunity to enhance their problem-solving skills as part of the iterative process that characterizes research and to enhance their data analysis skills.

Enhancement of their data analysis skills involved using the R programming language as well as the Python programming language to summarize the results of the experiments. The data analysis and problem-solving skills are valuable skills for students that will soon enter the job market, thus meeting the goals of providing workforce development opportunities as part of the research projects.

6.4 Technology Transfer

As part of the technology transfer efforts, a summary of the research project has been uploaded to the SAFER-SIM website. In addition to the summary, a webinar to present the research project to those interested will be hosted as part of the project completion requirements. Finally, data collected as part of the research will be made available through the Harvard Dataverse website.

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