Advanced Warning System for Safer Interaction Between Vehicles and Vulnerable Road Users

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ABSTRACT

A driving simulator experiment was used to study the impact of detecting pedestrians and bicyclists by participants with and without an advanced warning about the presence of the vulnerable road users ahead. The driving scenario included rural roadways, urban roadways and a 15-mph winding road. The warning system used to communicate the presence of vulnerable road user ahead was a combination of auditory cue and a simultaneous visual cue displayed on the dashboard. While twenty-one participants were recruited for the experiment, the analysis was performed for data collected from 19 participants. The participants were asked to detect the presence of pedestrians/bicyclists by pressing a button device on the steering wheel. The reaction distance between the location of an event and the location of detecting an event by the driver was used as the analysis measure. The warning system was activated at 20, 30, and 40 seconds ahead from reaching an event (pedestrians or bicyclists). When the warning system was activated, statistical tests suggest that participants detected the presence of pedestrians/bicyclists 25 ft earlier than when no warning system was activated. While no statistically significant difference was observed between the different activation locations of the warning system, the variances in the location where pedestrians/bicyclists were detected were lower when the warning system was activated. When the warning system was activated, for most events (approximately 73%), there was a speed reduction of 4.9 mph on average observed. No speed reduction was observed for the events with no warning system.

Keywords: driving simulator, vehicle-pedestrian interaction, in-vehicle warning system

INTRODUCTION

As the automotive industry moves toward autonomous vehicles, companies continue to develop cutting-edge systems that aim to make driving safer, more pleasant, and more convenient. While drivers operating traditional vehicles perceive the driving environment through traffic control devices, autonomous vehicles are equipped with systems that detect these devices. Until the time when autonomous vehicles are the only operating road vehicles, both traditional and self-driving vehicles will share the same roads. For this transitional phase, new systems are being created to provide a smooth and safe transition toward the total adoption of autonomous vehicles. Several car manufacturers have proposed many developments in the domain of Advanced Driver Assistance Systems (ADAS) to improve the interactions between driver and vehicle (*1*).

Some manufacturers and companies such as Continental (*2*), Navdy (*3*), Garmin (*4*), and others have already released devices and vehicles that adopt in-vehicle head-up display technology for showing navigational information as well as selected warning messages. Other manufacturers are offering augmented reality solutions by overlaying graphics and text information in the real life (*5*). These solutions help direct the driver's attention to roadside hazards, and help decrease the response time for detecting hazardous objects (*6*). Moreover, in-vehicle cues highlight important objects or regions and hence, enhance the visibility of some elements such as pedestrians and obstacles. These cues also help drivers take the correct action to avoid potential conflicts (*7*).

In-vehicle technology has improved over time and continues to improve. Advanced safety systems such as collision avoidance systems are examples of such advancement. As this technology continues to evolve and connected vehicle technology becomes omnipresent, 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 such scenario, these vehicles could provide drivers with an advanced warning of a potentially unsafe situation caused by the presence of an unexpected/vulnerable road user.

Pedestrians are among the most vulnerable users of the transportation system. The low visibility of pedestrians is often the cause of vehicle-pedestrian accidents along with other factors such as alcohol, drowsiness, speeding, or distraction (*8*). In-vehicle warning systems have the potential to communicate to drivers the presence of a potentially unsafe situation ahead prior to the driver realizing that danger on their own. For example, if a vehicle can communicate the presence of an unexpected pedestrian or bicyclist that is not yet visible to the user, that in-vehicle warning system could be a lifesaver. Pedestrian recognition can reduce the number of pedestrian injuries and fatalities by warning the driver. 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 using an in-vehicle interface.

The objective of this study is to evaluate the impact of an advanced audio-visual warning system that communicated the presence of pedestrians/ bicyclists at a significant distance ahead to drivers. The objective of the study was achieved by conducting a driving simulator experiment that exposes participants to situations in which pedestrians/bicyclists were not yet within the visual range of a driver.

LITERATURE REVIEW

Driving has become ubiquitous. However, the driving task is complex as it requires a wide range of skills and abilities. Time and pressure constraints force drivers to process a small percentage of audiovisual information at once. Most of the time drivers are able to handle the complexity of the driving task. However, due to inherent human physical, perceptual, and cognitive limitations, drivers make driving errors. In fact, driver error accounts for 75 to 95% of roadway crashes (*9*, *10*). Pedestrian fatalities are among the highest numbers in crashes caused by drivers. In 2016, 90 percent of the pedestrians fatalied were caused in a single-vehicle traffic crashes. On average, a pedestrian fatality was reported every 1.5 hours in traffic crashes in 2016 (*11*).

Pedestrians are among the most vulnerable road users, especially when crossing a roadway (*12*). Drivers tend to travel at constant maximum speeds with minimum delays and stops, whereas pedestrians are reluctant to wait at curbs for long times or to change their walking speeds or paths. A pedestrian-vehicle conflict situation is created when these two road users intersect. A study (*8*) looked at the driver-pedestrian interaction during the crossing conflict. Five cases were reported for drivers slowing down or stopping for crossing pedestrians: 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 study showed that female drivers and older drivers slowed down more than other drivers. Pedestrians are hit twice as often by vehicles turning left than 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 (*13*).

In-vehicle warning systems are recent technological advancement in the transportation field. In-vehicle warning systems can provide drivers with key information about the roadway conditions ahead. The most common types of in-vehicle displays are head-down display (HDD), head-up display (HUD), and augmented reality (AR) display (*14*). Head-down displays refer to displays positioned in the middle of the vehicle's control panel, whereas HUD project the required information directly into the driver's line of sight, i.e. the windshield (*14*). Augmented reality display is the most advanced technology and is a more advanced form of HUD that can project a virtual object on the road itself (*2*). In-vehicle systems interaction can increase safety while driving if minimal or no interaction stimulated visual demands (*15*). The driving simulator is used to evaluate the settings for in-vehicle systems and to measure of driver attention relevant to in-vehicle systems (*16*).

Pedestrian collision warning system (PCWS) is an in-vehicle system that is used to detect the presence of pedestrians and warn the driver about potential dangers. PCWS detects the presence of pedestrians and calculates collision time and determine the possibility of collision. PCWS alert the driver through beeps and sounds (*17*). A modified version of PCWS was designed and assessed in a driving simulator. A visual display in the form of an AR display was added to the system. The visual alert gave drivers a sensation that a pedestrian might cross the road which made drivers slowdown in some situations (*1*). However, theses systems are only activated when the pedestrian is in field of view.

METHODS

Participants

Twenty-one healthy participants, 15 males and 6 females, were recruited to participate in the driving simulator experiment. Recruited participants had a mean age of 30 years old (ranging from 21 to 70 years of age) and a standard deviation of 11.3. All participants had normal to corrected-to-normal vision and were licensed drivers with driving experience between 6 and 52 years. The oldest driver dropped out after the practice session due to simulation sickness concerns. One participant encountered a technical malfunction which prevented them from completing the experiment. Hence, collected data was available for 19 participants. Each participant was paid $20 for completing the experiment.

Apparatus

The Ford Fusion driving simulator located at the University of Wisconsin-Madison was used for data collection. Collected data includes, but is not limited to, speed, position, lane position, steering angle, brake pedal position, and gas pedal position. The vehicle state data is collected at a rate of 60 Hz. An additional instrumentation to the driving simulator was used to collect responses from participants. A Bluetooth™ device consisting of buttons was added to the steering wheel as shown in Figure 1.

Figure 1 – Push button

Procedure

Prior to participating in the experiment, each participant was shown the driving simulator and was given a consent form to read and sign. A 5-min practice session followed the consent form to let participants get familiar with the driving simulator. Each participant then drove the experimental scenario created to fulfill the goals of the study. The scenario involved rural cross sections (2.3 miles) followed by urban cross sections (2.1 miles). The driving simulator was set to emulate normal weather conditions (day driving, good visibility, no rain or snow).

In the rural portion of the scenario, participants were asked to follow a leading vehicle until that vehicle exited the roadway. The leading vehicle was used to set a low workload that drivers would experience in such an environment. In the urban portion of the scenario, participants were asked to follow navigation instruction posted as signs at signalized intersections. These custom signs provided guidance to participants regarding the turns to make and they are shown in Figure 2.

Figure 2 – Custom guide sign messages

For the duration of the experiment, participants were asked to press on the push button device (Figure 1) once they saw a pedestrian or a bicyclist. The time at which the participants pressed the push button was first logged on a mobile device with the Android™ platform using a commercially available application named Automate. The logged time was then expressed as a function of the simulator time. In total, participants were expected to click 7 times for events that included a bicyclist or a pedestrian.

The 7 events were presented in the following order: a bicyclist driving on rural freeway shoulder (1 event), a bicyclist driving on a 15 mph street (1 event), a pedestrian hitchhiking after a winding road (1 event), 2 pedestrians crossing on a straight street (1 event), and 2 pedestrians crossing after a curve (3 events).

Experimental design

A between-participants design was used to evaluate the impact that a warning system communicating the presence of a pedestrian/bicyclist ahead have on the detection of the pedestrian/bicyclist by a driver. The warning system was a combination of visual and auditory cues. The visual message was displayed on the dashboard as shown in Figure 3. Each visual cue was followed simultaneously by a auditory cue in the form of a beep.

Figure 3 – No alert displayed (left) versus alert displayed (right)

The detection task was evaluated in a variety of workload environments: driving through a rural freeway cross section while following a car (medium workload), navigating through a 15 mph winding road (high workload), and navigating through a typical urban environment (low workload).

A total of 140 events were identified (initially designed for 20 participants). Participants were randomly and evenly placed into 2 groups: control and treatment group. In 50% of the events, participants did not receive a visual and auditory cue about the presence of a pedestrian/bicyclist and were placed in the control group. For the remaining 50% of the events, an auditory and visual warning system was triggered. The warning system was triggered as a function of time-to-arrival to an event position calculated based on the vehicle speed. The warning system was activated when the calculated time-to-arrival was 20, 30, or 40 seconds (pre-defined in the scenario).

RESULTS AND DISCUSSION

The reaction to an event was calculated as the distance between the location of detection of an event (identified by the bush button device) and the location of an event in the scenario. A total of 135 experimental data points were available for analysis from the 19 participants. For each participant, data was visually inspected to remove missing performance measures. This is due to participants not detecting an event, usually the first one. The median absolute deviation (MAD) was then used as the statistical filtering method to identify outliers. The median, a central trend indicator, is considered a resistant estimator and is very insensitive to outliers' presence in the sample. Density plots, Q-Q plots and Shapiro test were then used to investigate the normality of the data. Because the data deviated from a normal distribution, the non-parametric Kruskal-Wallis test was used to compare the means of more than two groups. When a statistical significance was reported, the non-parametric pairwise Mann-Whitney Wilcoxon test was used to compare between two groups.

Results of Distance -Based Analysis

Each driver reacted differently to seeing a pedestrian/bicyclist. Figure 4 show the location of the driver in X and Y coordinates along the road while approaching each of the 7 events.

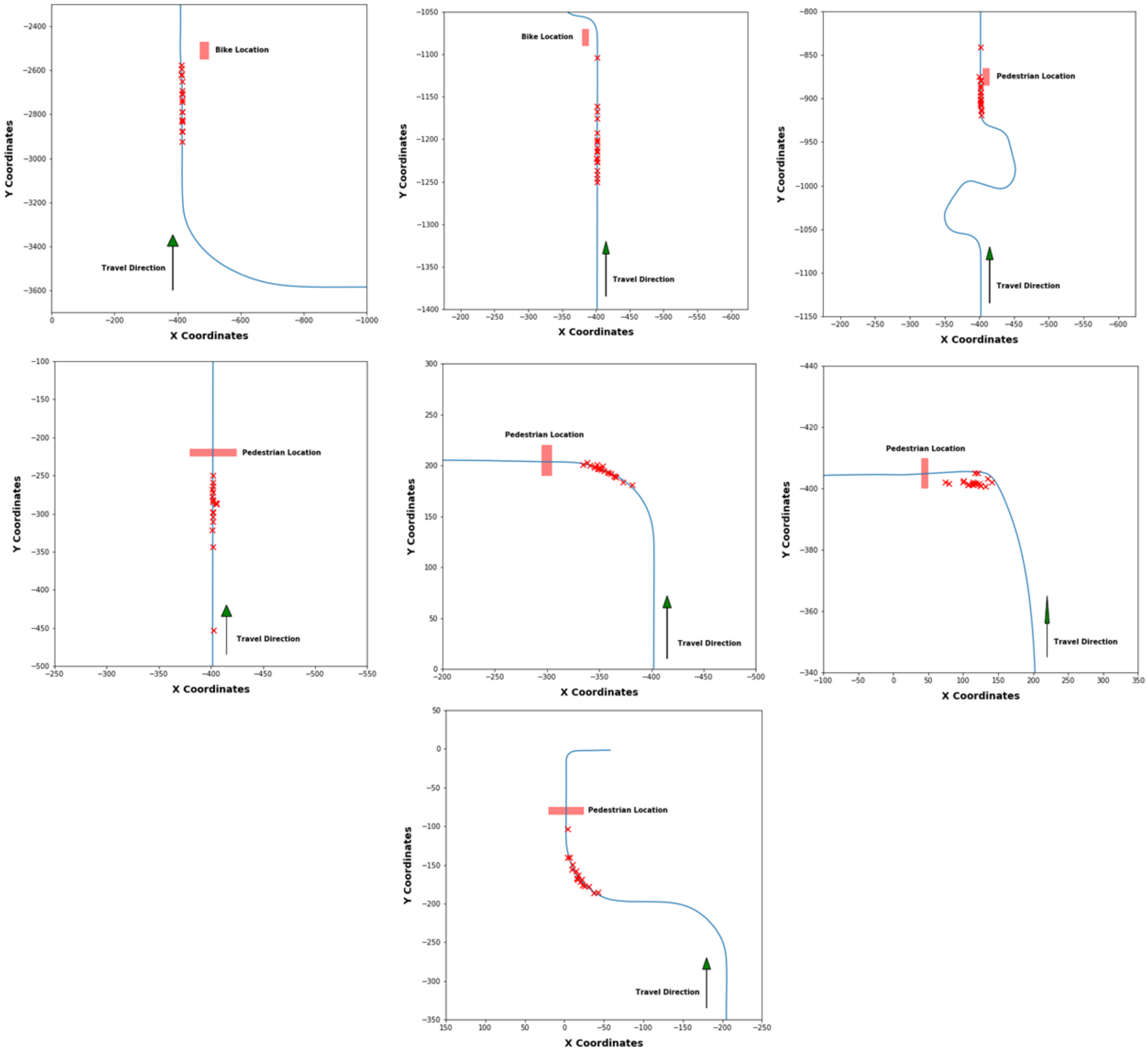

Figure 4 – Location of pedestrian/bicyclist detection

The filtered data was analyzed as a whole set, and the control group was compared against the three different activation time of the warning system. Similar analysis was conducted for each event. The data was also grouped into 3 categories based on the workload: rural, urban, and winding road. Similar statistical analysis was performed for each category. To visually summarize the data, a box plot is shown in Figure 5 and selected summary statistics are presented in Table 1. The average reaction distance for events without the warning system was 93.72 meters (307.5 ft), whereas the average reaction distance was 103.85 meters (340.7ft), 93.61 meters (307.1 ft), and 107.88 meters (353.9 ft) for events with the warning system activated at 20, 30 and 40 sec from the arrival time to the event, respectively.

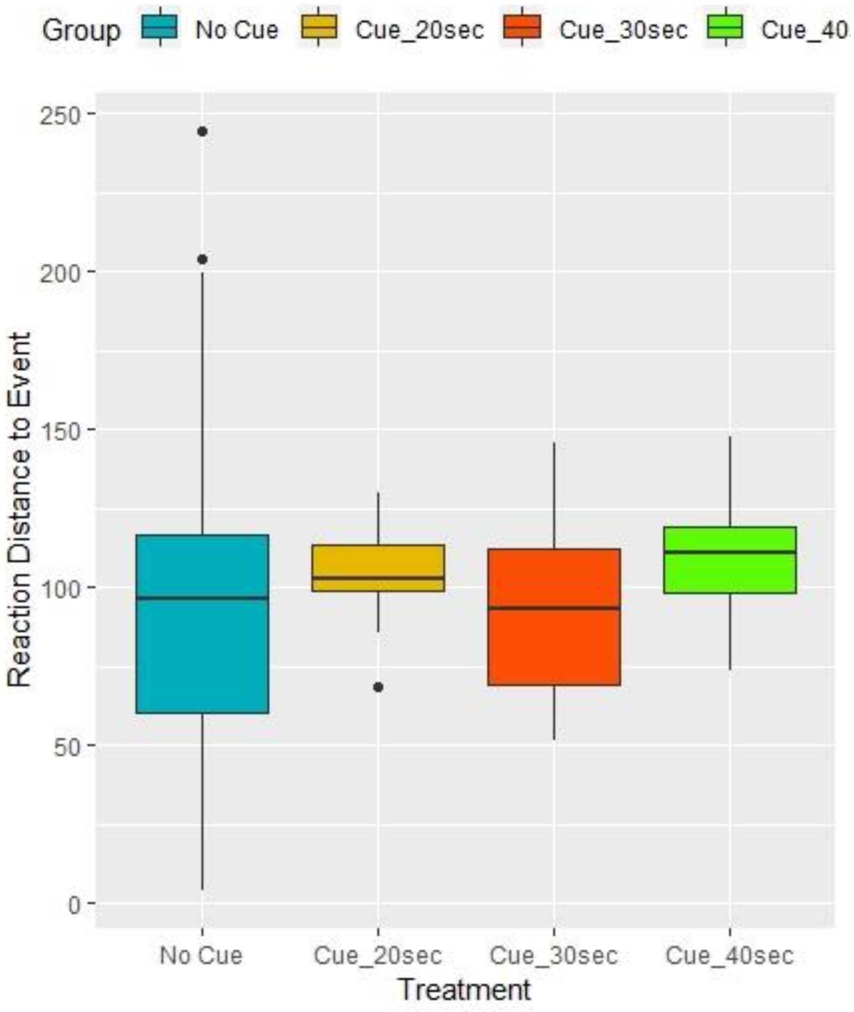

Figure 5 – Box plot per group

Table 1 – Summary statistics for the dataset (control versus each treatment)

	Control group	Time-To-Arrival to an Event		
		20 sec	30 sec	40 sec
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			

The Kruskal-Wallis test resulted in a large p-value indicating no statistically significant difference between the mean reaction distances of groups. Because no statistically significant difference was found, the 3 treatment groups can be grouped in one group, and additional analysis can be carried out. Selected summary statistics for control and warning system groups are shown in Table 2. A one-sided Wilcoxon test was used to compare between the two groups (alert/no alert). The result showed a statistically significant difference between the mean reaction distances of both groups. It should be noted that this mean difference is 7.8 m, which is equivalent to 25.6 ft.

Table 2 – Summary statistics for the dataset (control versus all treatments)

	Control Group (no alert)	Warning System (alert)
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	

The Kruskal-Wallis test was performed for each event to check for significant difference in reaction distance between the absence of the warning system and the 3 activation times of the warning system. The p-value ranged between 0.1 and 0.87 meaning that there exists no statistically significant difference between the reaction distance means of the control and treatments for each event.

With no statistically significant difference, the 3 treatments were combined into one group called alert. The Wilcoxon test was then used to check for significant difference between the reaction distance means of alert/no alert (control) groups for each event. The event that involved pedestrians crossing on a straight street was the only event that showed a statistically significant difference between the distance means of the alert and no alert groups with a p-value of 0.023. The difference is 21.6 m, which is equivalent to 70.9 ft.

The data was also grouped into 3 categories based on the workload: rural, urban, and winding road (15 mph). The reaction distance means between the control and the treatment groups were investigated by the Kruskal-Wallis test. The p-values were 0.75, 0.96, and 0.64 respectively leading to no statistically significant difference between the reaction distance means of no alert and any treatment alert. Hence, all treatments were grouped into one group (alert), and a one-sided Wilcoxon test was then performed. No statistically significant difference between the distance means of the two groups, no alert versus alert, was found.

Results of Descriptive Statistics for Speed-Based Analysis

For each participant, a speed profile for each run was plotted. The profile also included the activation time of the warning system along with the moment the participant clicked the push button when they detected a pedestrian or bicyclist. An example of such a profile is shown in Figure 6.

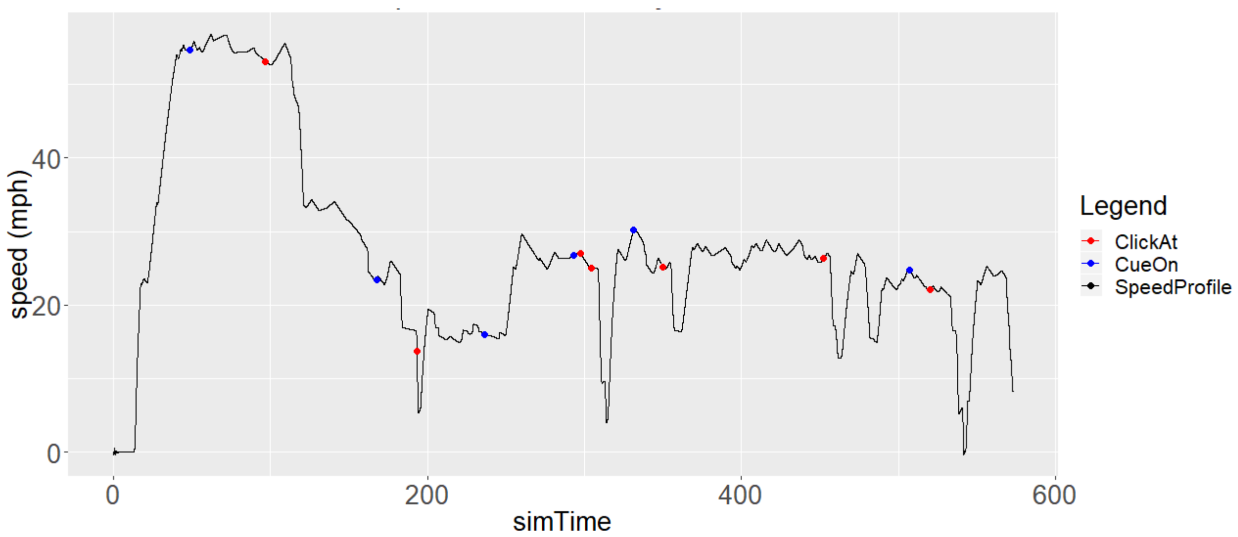

Figure 6 – Speed profile example (Participant 10)

Looking at the speed profiles for the 19 participants, drivers reduced their speed for 72.3% of the events after receiving the warning system about a pedestrian/bicyclist ahead. Drivers reduced their speeds for an average of 14 seconds after the activation the warning system. This reduction in speed shows that once drivers are alerted to an event, they reduce their speed and pay more attention to their surroundings. For each alert treatment, a summary of statistics is shown in Table 3.

Table 3 – Duration of speed decrease in seconds per alert treatment

	Time-To-Arrival to an Event		
	20 sec	30 sec	40 sec
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 reduced their speeds to below posted speed limit, which gave them more time to travel. For example, although the warning system was activated 20 seconds prior to the reaching an 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 and the values ranged between 0.5 to 21.1 mph. A high value of speed reduction corresponds to participants originally driving above posted speed limit. Then, once the warning system was activated, they reduced their speed to match the posted speed limit.

CONCLUSIONS

A driving simulator experiment was conducted to study the impact of a warning system communicating the presence of a pedestrian/bicyclist ahead. The experiment only focused on communicating the presence of pedestrians/bicyclists that were not yet within the visual range of a driver. The distance at which pedestrians/bicyclists were detected by the participants was compared for groups of events associated with the lack or the presence of the warning system activated at different times. The warning system was activated at 20, 30, and 40 seconds ahead from reaching an event (pedestrians or bicyclists). When the warning system was activated, statistical tests suggest that participants detected the presence of pedestrians/bicyclists 25 ft earlier than when no warning system was activated. However, this average distance was the result of grouping different speed zones (rural freeway, urban street, low speed winding road). No statistical difference was observed when individual speed zones were analyzed, except for a scenario in a pedestrian was crossing the road instead of a pedestrian/bicyclist moving along the road. In addition, for situations with high workload (winding road), participants focused more on the driving task and did not pay attention to the warning system. While no statistically significant difference was observed, the variances in the location where pedestrians/bicyclists were detected are lower when the warning system was activated. Lower variances might suggest that, when the warning system is activated, behavior is more predictable; that could be attributed to participants paying more attention to the roadway conditions. The behavior related to the speed of participants was also observed. When the warning system was activated, for most events (approximately 73%), there was a speed reduction of 4.9 mph on average observed. No speed reductions were observed near the location of the events when the warning system was not activated.

The analysis of the results suggests that the sample size may be one of the limiting factors of the experiment. Therefore, future work should focus on expanding the sample size per event. In addition, the driving simulator itself is a limiting factor because of the complexities of the experiment. Hence, a lower-fidelity experiment could be conducted to assess the spatial effectiveness of such warning system on the attention of participants. The lower-fidelity experiment could be conducted using dynamic surveys that expose participants to a pre-recorded driving scenario via a computer screen.

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AUTHOR CONTRIBUTIONS

The authors confirm contribution to the paper as follows: study conception and design: H. Nassereddine, K. R. Santiago-Chapparo, D. A. Noyce; data collection: H. Nassereddine; analysis and interpretation of results: H. Nassereddine, K. R. Santiago-Chapparo; draft manuscript preparation: H. Nassereddine. All authors reviewed the results and approved the final version of the manuscript.

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