Safely and Effectively Communicating Non-Connected Vehicle Information to Connected Vehicles through Driving-Simulator-Based Research

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ABSTRACT

A driving simulator experiment was conducted to evaluate the effectiveness of a warning system that communicate the presence of a potential non-connected red-light-running vehicle to the driver of a connected vehicle (CV). The warning system was a combination of an auditory cue followed simultaneously by a visual message displayed on the windshield as HUD. Twenty participants were recruited to partake in the driving simulator experiment. Participants were exposed to an imminent collision scenario with a non-connected red-light-running vehicle. Participants were randomly placed in a control group and 3 treatment groups and their response to the scenario was studied. For the control group, the warning system was activated at the stop bar, whereas for the treatment groups, the warning system was activated at 50 ft, 100 ft, and 150 ft from the stop bar. The reaction time to the warning system was collected and Kruskal-Wallis test was used to investigate the significance in the differences of means. The results showed a statistically significant difference in the mean of reaction time between the different groups. Mann-Whitney Wilcoxon test was used to compare between two groups. Drivers reduced their speeds for an average of 2.15, 2.24, 2.59, and 3.15 sec when the warning system was activated at the stop bar and 50, 100, and 150 ft before the stop bar, respectively. Participants came to a complete stop for 29.73%, 17.5%, 29.27%, and 47.7% of the events at the stop bar and at 50, 100, and 150 ft before the stop bar, respectively.

Keywords: driving simulator, warning system, red-light running vehicle

INTRODUCTION

Driving requires requires full attention and awareness to process a large amount of information related to the roadway and the surrounding environment under time and pressure constraints (*1*). Drivers are prone to making mistakes due of inherent human physical, perceptual, and cognitive limitations. In fact, driver error has been identified as the main cause in 75-95% of roadway crashes (*2*, *3*). Around 40% of motor vehicle crashes in the US occur at intersections (*4*). Noncompliance with traffic control devices is one factor contributing to such crashes, with red-light running being a frequent cause of crashes at signalized intersections (*4*–*6*). Disobeying traffic signals at signalized intersections is one of the major hazards to road safety is drivers. A high percentage of severe road crashes occur at intersections and a high percentage of these crashes are due to drivers disobeying or “running” the red light (*7*). Red-light violation has high rates at busy urban intersections, and the highest rates have been recorded during peak hours. Running the red light causes an estimated 165,000 injuries and 800 fatalities each year. Half of the fatalities are pedestrians and people in vehicles that are hit by red-light runners (*8*).

Several vehicles are now equipped with driving aids or advanced driver-assistance systems. These assistance systems are refered to in-vehicle technology. In-vehicle technology has improved over time, and these advancements have led to the inclusion of active safety systems that can help drivers avoid collisions. The market for in-vehicle systems has grown in the past years. In-vehicle technology includes Bluetooth™-to-voice-command systems and information display systems. Several in-vehicle display systems have been tested for both commercial and research applications. The most common types of in-vehicle displays are head-down display (HDD), head-up-display (HUD), and augmented reality (AR) display (*9*–*13*). Head-up displays project the needed information directly into the windshield, which is the line of sight of the driver. Hence, drivers receive information without taking their eyes off the road (*9*). 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 (*14*–*16*). Head-up displays reduce driver distraction and increase driver safety as they display the necessary information when needed.

In-vehicle technology represents a key element in the human-machine interface. Advanced in-vehicle technologies present great potential in offering information such as navigation, logistics, and safety measures to drivers at the needed time. In-vehicle technology has grown over time and continues to improve. Several studies have examined the effectiveness of in-vehicle systems (*17*, *18*). Studies have used driving simulators and real traffic driving to evaluate in-vehicle systems. For example, a full-windshield HUD system was used to detect and highlight road signs. The system was shown to help drivers navigate more easily in complex driving situations (*19*). Studies have shown that in-vehicle systems can increase safety while driving if driver-system interaction did not impact visual demands (*20*).

Connected vehicles (CVs) can increase highway safety by relying on numerous sensors to receive information from roadway infrastructure and other vehicles. Several hypothetical safety improvements from CV exist. Such improvements include the ability to receive information about icy conditions and crashes ahead and the ability to receive information about a potential red-light runner and communicating that message to the driver, thus enabling a potential avoidance maneuver. Unfortunately testing such scenario on roads requires high market penetration of CVs which is not likely in the immediate future. However, taking advantage of existing infrastructure and exploring the safety improvements with the CV technology is possible.

Arguably, in-vehicle sensors should be able to detect a potential red-light runner. However, in-vehicle sensors can be the victims of blocked lines of sight due to the presence of other vehicles, pedestrians, and roadside infrastructure, thus creating "blind spot" scenarios. For example, when making a right turn on red, a vehicle on the left adjacent lane can block the view of potentially conflicting vehicles. Similarly, when making a left turn, a vehicle on an opposing left turn bay can block the view of conflicting vehicles. The collaborative nature of CV technology can address these line-of-sight limitations.

The objective of this study is to evaluate the effectiveness of an advanced in-vehicle audio-visual warning system in communicating the presence of a potential non-connected red-light-running vehicle crossing from a blind spot. To achieve this objective, a driving simulator experiment was conducted. Participants were exposed to an imminent scenario in which a non-CV is running a red light from a blind spot as shown in Figure 1.

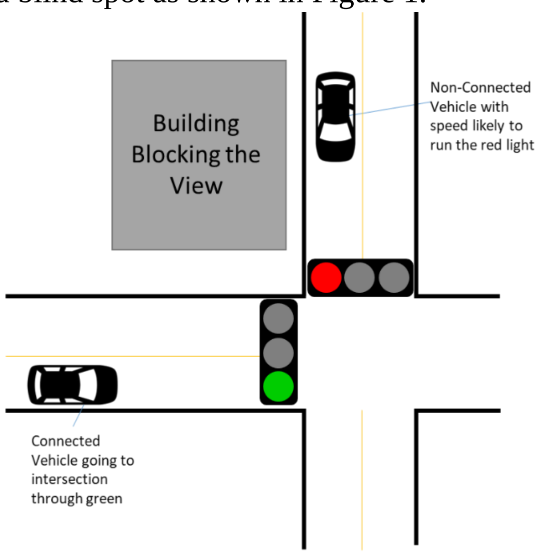


Figure 1 – Blind spot scenario example

METHODS

Apparatus

The experimental procedures were conducted on a full-scale, state-of-the-art, Ford Fusion driving simulator located at the University of Wisconsin-Madison. Participants can interact with the virtual roadway environment projected by the simulator and drive as if they were on a real roadway. Vehicle performance data such as speed, lane position and steering angle is collected at a rate of 60 Hz as a typical operation of the driving simulator.

A separate instrumentation device was used to collect responses from participants for a secondary task. The instrumentation involved the use of a Bluetooth push button device shown in **Error! Reference source not found.**. The participants were asked to press the buttons on the device when they saw a pedestrian.

Experimental design

A between-participants design was used to evaluate the effectiveness of a warning system about the presence of a potential non-connected red-light-running vehicle. The in-vehicle warning system was a combination of auditory and visual cues. Figure 2 shows the visual warning message that was displayed on the windshield as a HUD. During the experiment, the warning system was triggered based on a pre-defined experimental matrix.

Participants were randomly placed in 4 groups: a control group, and 3 treatment groups. For participants in the control group, the warning system was activated at the stop bar. As for participants in the treatment groups, the warning system was activated at a distance of 50 ft, 100 ft, or 150 ft from the stop bar. The participants were distributed evenly in the control and each treatment group. One-quarter of the participants was randomly placed in the control group. Similarly, one-quarter of the participants was randomly placed in each of the 3 treatment groups.

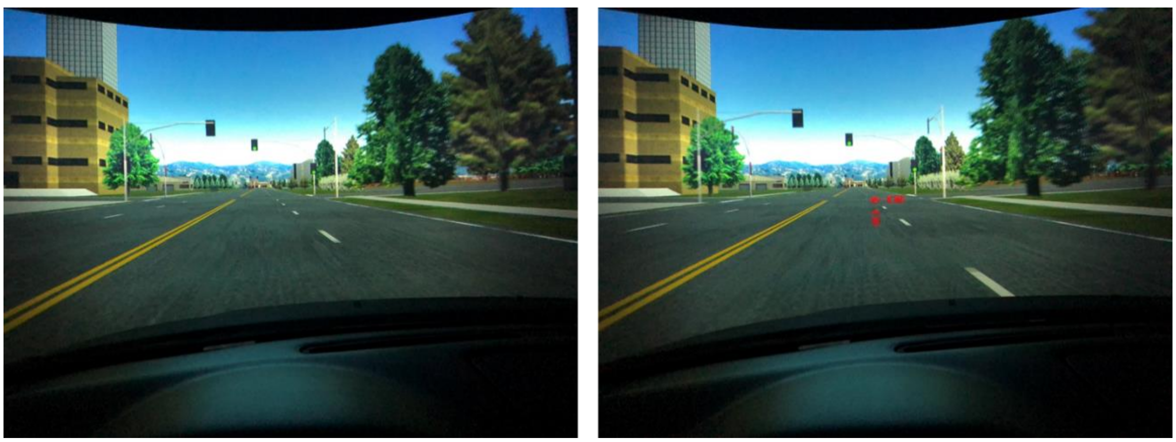


Figure 2 – No alert displayed (left) versus alert displayed (right) as a HUD

Procedure

Before participating in the experiment, participants were shown the driving simulator and then were asked to read and sign a consent form. After signing the consent, participants drove a practice session for 5 minutes in the simulator and then proceeded to participate in the experiment.

The experiment consisted of 3 small runs (1454 m, 1471 m, and 963 m). On average, runs 1, 2, and 3 took 3 min 29 sec, 3 min 6 sec, and 2 min and 24 sec, respectively. The driving scenario involved an urban roadways cross-section and the driving simulator was set to emulate normal weather conditions (day driving, good visibility, no rain or snow).

Participants

Twenty healthy drivers participated in the data collection process. The mean age of recruited participants was 32 years (ranging from 19 to 75 years of age) with a standard deviation of 13.7. The gender of the participants was equally distributed between male and females (10 participants each). All participants were licensed drivers with between 1 and 52 years of driving experience.

All participants had normal or corrected-to-normal vision. The participants were given a cash reward of $20 for the experiment.

None of the participants had simulation sickness during the practice session. However, the oldest driver dropped out after driving one third of the first run due to simulation sickness concerns. The youngest driver and another participant dropped out after completing the first run, while two other participants dropped out after completing two runs due to simulation sickness concerns.

Driving tasks

Participants were asked to drive as if they were on a real road and follow the main road without making any turns. While driving, participants encountered non-CVs running a red light, and they reacted accordingly. To mimic a real driving situation, participants were assigned a secondary task to keep them engaged while driving. For the secondary task, participants were asked to press the push button (**Error! Reference source not found.**) once they identified a pedestrian. In total, participants had to react to 9 non-CVs running the red light and to click 13 times for the secondary task involving a pedestrian.

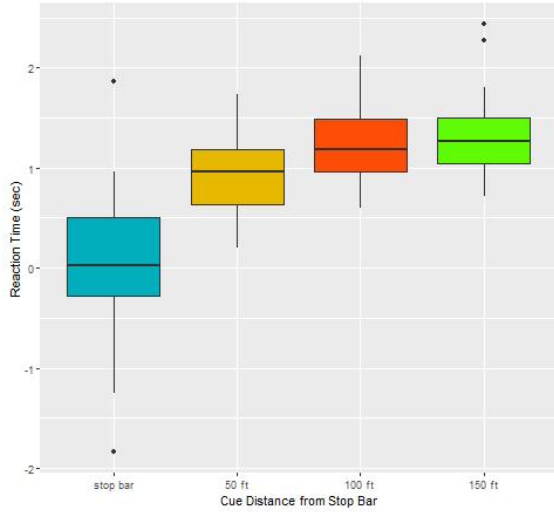
RESULTS AND DISCUSSION

A total of 154 experimental data points were available for analysis from the 20 participants. For each participant, the data was first visually inspected to remove anomalous performance measures resulting from participants driving way below the speed limit. A slow driving behavior led to the absence of the imminent collision scenario with the red-light-running vehicle designed for the purpose of this research; hence, the warning system was not activated as expected.

The median absolute deviation (MAD) was then used as the statistical filtering method to identify outliers. The filtered data was then inspected for normality to determine the appropriate test to use. With the normality assumption violated, the non-parametric Kruskal-Wallis test was used to compare the means between the control and the 3 treatments groups. When a statistical significance was reported, the non-parametric pairwise Mann-Whitney Wilcoxon test was used to compare between two groups.

Results of Reaction-Time-Based Analysis

Each participant reacted differently when they were exposed to an imminent collision situation with a red-light-running vehicle. The reaction time to the red-light-running vehicle was calculated from the moment the warning system was activated. The reaction time was then compared between study groups associated with the different locations of activation of the warning system, i.e. at the stop bar, 50 ft, 100 ft, and 150 ft before the stop bar. A density plot and a box plot are shown in Figure 3 and Figure 4 to visually summarize the data for each group. When the warning system was activated at the stop bar, the average reaction time was 0.0515 sec. Most drivers saw the red-light-running vehicle and reacted to it before the activation of the warning system, which led to negative reaction time. When the warning system was activated at a distance 50 ft, 100 ft, and 150 ft before the stop bar, the reaction time was 0.942 sec, 1.22 sec, and 1.31 sec, respectively.



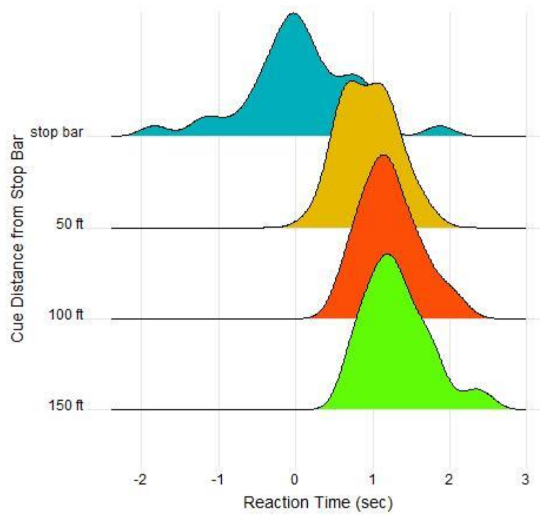


Figure 3 – Density plot per warning system group

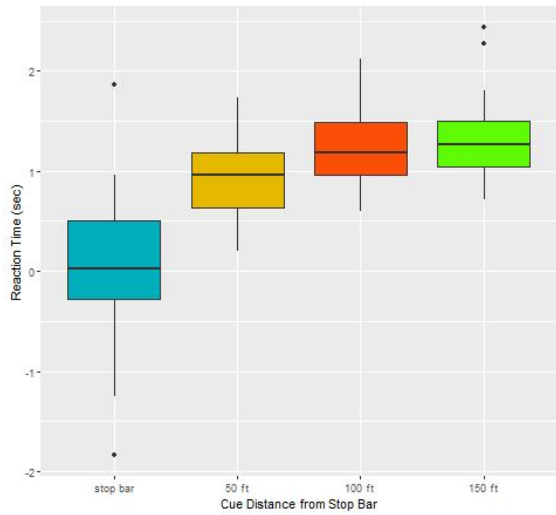


Figure 4 – Box plot per warning system group

For each group, selected summary statistics are shown in Table 1. These values are for the whole dataset after removing outliers.

Table 1 – Summary statistics for the dataset

(all data) Reaction time to warning at:				
	Stop Bar	50 ft before the stop bar	100 ft before the stop bar	150 ft before the stop bar
Sample Size	34	37	39	31
Mean	0.0515	0.942	1.22	1.31
Standard Deviation	0.709	0.353	0.376	0.422
Median	0.025	0.967	1.18	1.27
IQR	0.775	0.550	0.525	0.458
p-value – Kruskal-Wallis test	3.809e-14			

A small p-value (less than 0.05, 0.1 and 0.001) resulted from the Kruskal-Wallis test that was used to compare the reaction time means between the different locations at which the warning system was activated. Hence, enough evidence exists from the sample to indicate that the reaction time differs between groups and the location of the warning system is statistically significant at the 95

(99 and 99.9) percent confidence level. The pairwise Mann-Whitney Wilcoxon test was then used to determine the statistically significant pairs. The results showed a statistically significant difference in reaction time between a warning system activated at a stop bar and a warning system activated at 50 ft, 100 ft, and 150 ft before the stop bar. A statistically significant difference in reaction time between a warning system activated at 50 ft and a warning system activated at 100 ft and 150 ft was also reported, as shown in Table 2.

Table 2 – Pairwise comparisons using the Wilcoxon test

	Stop Bar	50 ft before stop bar	100 ft before stop bar
50 ft before stop bar	1.6e-07	-	-
100 ft before stop bar	4.9e-10	0.0149	-
150 ft before stop bar	2.8e-09	0.0033	1.0000

After investigating the data as a whole, the same statistical procedure was carried out for each of the two directions traveled by the red-light-running vehicle. A summary of statistics per direction traveled by the red-light-running vehicle is shown in Table 3.

Table 3 – Summary statistics per direction traveled by the red-light-running vehicle

	Red-Light Runner Traveling Westbound				Red-Light Runner Traveling Eastbound			
	Reaction time to warning at:							
	Stop Bar	50 ft before the stop bar	100 ft before the stop bar	150 ft before the stop bar	Stop Bar	50 ft before the stop bar	100 ft before the stop bar	150 ft before the stop bar
Sample Size	25	23	27	22	11	14	13	9
Mean	0.382	1.03	1.28	1.26	-0.541	1.21	1.21	1.44
Standard Deviation	0.679	0.342	0.508	0.375	0.636	0.285	0.285	0.521
Median	0.267	1.03	1.18	1.16	-0.417	1.27	1.27	1.48
IQR	0.817	0.467	0.567	0.392	0.867	0.467	0.467	0.433
p-value – Kruskal-Wallis test	2.564e-07				1.184e-05			

The results of the Kruskal-Wallis test showed a p-value less than 0.05 (0.1 and 0.001) for each travel direction. This result indicates a statistically significant difference, at the 95 (99 and 99.9) percent confidence level, in the reaction time among the different activation locations of the warning system. The pairwise Mann-Whitney Wilcoxon test was then performed (Table 4). The results showed a statistically significant difference in reaction time between a warning system activated at a stop bar and a warning system activated 50 ft, 100 ft, and 150 ft before the stop bar for both directions of travel. Contrary to the whole data analysis, no statistically significant difference was reported in the reaction time between a warning system activated at 50 ft and a warning system activated at 100 ft and 150 ft for both directions of travel.

Table 4 – Pairwise comparisons using Wilcoxon test per direction traveled by the red-light-running vehicle

		Stop Bar	50 ft before the stop bar	100 ft before the stop bar
Red-Light Runner Traveling Westbound	50 ft before the stop bar	0.00043	-	-
	100 ft before the stop bar	1.3e-05	0.49850	-
	150 ft before the stop bar	2.1e-05	0.48189	1.00000
Red-Light Runner Traveling Eastbound	50 ft before the stop bar	0.00023	-	-
	100 ft before the stop bar	0.00023	1.00000	-
	150 ft before the stop bar	0.00118	1.00000	1.00000

Results of Descriptive Statistics Speed-Based Analysis

For each participant, speed profiles were plotted for each run. In addition to the driver's speed, the moment the warning system was activated was shown on the same speed profile. An example of such a profile is shown in Figure 5. Although the red-light-running vehicle crossed from a blind spot, participants saw that vehicle and reacted to it before the activation of the warning system at the stop bar as displayed in the left image. This is due to the fact that the red-light-running vehicle became visible to the driver around the stop bar area and was no longer in the blind spot. The right image shows the activation of the warning system 30 ft before the stop bar. The participant reacted to the warning system and reduced their speed before seeing the red-light-running vehicle. They kept a low speed until the red-light running vehicle cleared the intersection.

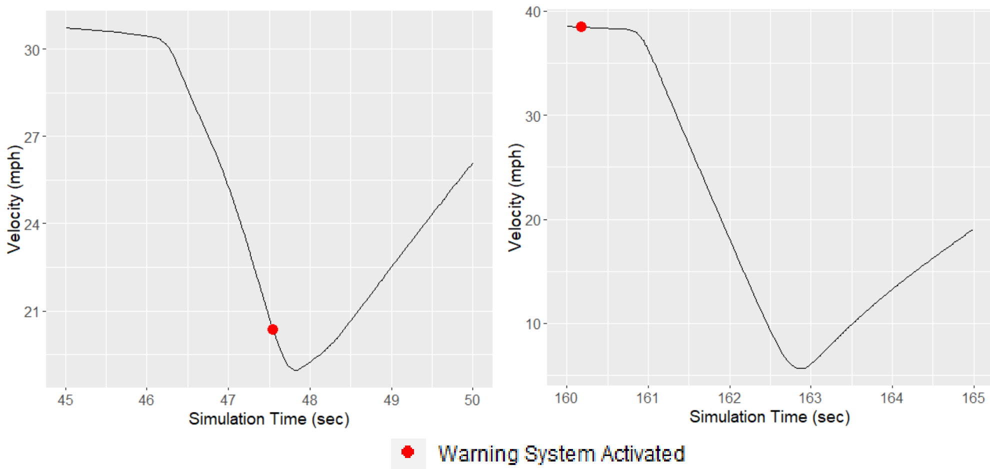


Figure 5 – Speed profile example with warning system activation moment: at a stop bar(left) and at 30 ft before the stop bar (right)

Looking at the speed profiles for the 20 participants, drivers reduced their speed after the activation of the audio-visual warning system. When the warning system was activated at the stop bar and at 50, 100, and 150 ft before the stop bar, drivers reduced their speeds for an average of 2.15, 2.24, 2.59, and 3.15 sec, respectively. Some participants came to a complete stop after receiving the warning system. Participants came to a complete stop for 29.73%, 17.5%, 29.27% and 47.7% of the events at the stop bar and at 50, 100, and 150 ft before the stop bar, respectively. Similar statistics are available for each travel direction of the red-light-running vehicle, and the results are shown Table 5.

Table 5 – Summary of speed-based analysis

	Duration of speed reduction (sec)				**Percentage of a complete stop (%)**			
	Stop Bar	50 ft before the stop bar	100 ft before the stop bar	150 ft before the stop bar	Stop Bar	50 ft before stop bar	100 ft before stop bar	150 ft before stop bar
Red-Light Runner (all)	2.15	2.24	2.59	3.15	29.73	17.5	29.27	47.7
Red-Light Runner	2.14	2.52	2.71	2.88	30.77	8	44.44	48

traveling Westbound								
Red-Light Runner traveling Eastbound	2.17	1.79	2.38	3.78	27.27	33.33	0	27.27

Results of Secondary Task

Participants were asked to press on the push button device (**Error! Reference source not found.**) every time they detected a pedestrian. In total, participants were expected to detect 13 pedestrians distributed as follow: 7 in the first run, 2 in the second run, and 4 in the third run. Table 6 shows the results of detecting pedestrians while driving. For the first run, pedestrians were distributed all over the simulation run. Participants were able to detect only 70.71% of pedestrians. This result indicates that the participants were focusing on driving rather than looking around. For the second run, pedestrians were located near two intersections. Participants paid more attention around that area, especially at a red light and were able to detect 85.29% of the pedestrians. For the final run, pedestrians were placed in low-traffic areas. Participants were able to detect 91.67% of the pedestrians because of the low workload during driving. In total, participants were able to detect 70.38% of the pedestrians, which means that participants focused more on driving and paid attention to pedestrians when necessary.

Table 6 – Secondary task results

	Run 1	Run 2	Run 3	Total
Average	4.95	1.70	3.67	9.15
Expected	7	2	4	13
Percentage	70.71	85.29	91.67	70.38

CONCLUSIONS

This study examined an in-vehicle warning system at signalized intersections for situations in which a conflicting non-CV ran a red light from a blind spot. The warning system was not activated when a conflicting non-CV ran a red light within the visual range of the participant. A driving simulator was used to study the effectiveness of such warning system. An auditory cue followed simultaneously by a visual message displayed on the windshield as a HUD was used to communicate the presence of a conflicting non-CV running a red light to drivers. The warning system was activated at the stop bar and 50 ft, 100 ft, and 150 ft before the stop bar. In addition to reacting to the warning system, participants were expected to detect pedestrians as a secondary task. The reaction time to the red-light-running vehicle was calculated from the moment the warning system was activated. An average reaction time of 0.0515 sec resulted for the activation of the warning system at the stop bar. The low value is due to participants seeing and reacting to the red-light-running vehicle before the activation of the warning system at the stop bar. The average reaction time for events with a warning system 50 ft, 100 ft, and 150 ft before the stop bar was 0.942 sec, 1.22 sec, and 1.31 sec, respectively. The Kruskal-Wallis test showed a statistically significant difference in the mean of reaction time between the different groups. Similar results were reported when grouping the data by the direction of travel of the red-light-running vehicle. Drivers reduced their speeds for an average of 2.15, 2.24, 2.59, and 3.15 sec when the warning system was activated at the stop bar and 50, 100, and 150 ft before the stop bar, respectively. Some drivers came to a complete stop. Participants came to a complete stop for 29.73%, 17.5%, 29.27%, and 47.7% of the events at the stop bar and at 50, 100, and 150 ft before the stop bar, respectively. Combining all the results, the research team suggests activating such a warning system 50 ft or 100 ft before the stop bar. As for the secondary task, participants were able to detect 70.38% of the pedestrians. This result shows that participants focused more on the driving task and paid attention to pedestrians when necessary. The small sample size was a limitation is this study. Therefore, expanding the sample size is for future work. Future work can also look at different locations of displaying the warning system.

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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, J. Riehl, 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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