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

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Abstract

The largest safety impact of connected vehicle (CV) technology will occur only when a critical mass of vehicles and infrastructure is connected. This will require significant market penetration and improvements to our infrastructure, and it is occurring at a relatively slow pace compared to autonomous vehicle technology. Until CVs are ubiquitous, strategies for communicating between CVs and non-CVs as well as with connected infrastructure will be critical in improving transportation safety. Communicating information from roadway infrastructure to CVs is key, especially for scenarios in which the line of sight of in-vehicle sensors is obstructed by other vehicles, pedestrians, buildings, etc.

As part of the research project, the effectiveness of a potential warning system to communicate the presence of a likely red-light-running vehicle to the driver of a CV was evaluated. Red-light running was selected as a test scenario because non-CVs who run a red light could be detected by existing roadway infrastructure, even when not detected by sensors in CVs. The motivation for studying the effectiveness of a warning message is to provide the driver of a CV with a warning message (and the opportunity to react) prior to the point of engaging collision-avoidance features that are becoming standard in vehicles.

The evaluation of the effectiveness of a warning system was conducted using a driving simulator experiment. In the experiment, participants were exposed to an imminent collision scenario with a red-light-running vehicle. The response to the scenario for a control and treatment group were studied. Participants in the control group received a warning about the potential red-light-running vehicle at the stop bar. Participants in the treatment group received a warning message displayed as a head-up display at 50 ft, 100 ft, and 150 ft from the stop bar. The warning message was accompanied by an auditory warning.

A separate component of the project evaluated the feasibility of communicating the presence of a potential non-connected red-light-running vehicle to CVs using a radar-based vehicle-detection system. The feasibility of detecting red-light runners has been previously demonstrated, and the underlying data is discussed in the report. A strategy for communicating field data to dedicated short range communications units is presented.

1 Introduction

Connected vehicles (CVs) can increase highway safety by taking advantage of numerous sensors, information received from roadway infrastructure, and information from other vehicles. In fact, countless hypothetical safety improvements from CVs exist, such as the ability to receive information about icy conditions and crashes ahead. Another hypothetical safety improvement scenario includes a CV receiving information about a potential red-light runner and communicating that message to the driver, thus enabling a potential avoidance maneuver. Unfortunately, making such a scenario a reality requires high market penetration of CVs, something that does not seem likely in the immediate future. Therefore, in order to increase adoption of CV technology, the potential to materialize some of the safety improvements possible with the technology by taking advantage of existing infrastructure should be explored.

Radar-based vehicle detection (RVD) systems are arguably one of the most underused components of the transportation system infrastructure. These detection systems are typically installed at signalized intersections to monitor the presence of vehicles within a predefined zone by emulating loop detectors, but they also have the capability to continuously track the position and speed of vehicles approaching an intersection. Position and speed are key components of the basic safety messages (BSM) that can be received by CVs through technology like direct short-range communications (DSRC). Through a software-based approach, RVD systems could be used to mimic a CV and send non-CV information to nearby CVs, thus synthetically increasing the effective market penetration of the technology. For example, if an RVD detects a potential red-light runner, it could communicate that information to vehicles within the intersection, thus materializing the safety of CV technology under low-market-penetration scenarios.

Arguably, in-vehicle sensors should be able to detect a potential red-light runner. However, in-vehicle sensors, just like many key components of the transportation infrastructure, 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, but that will not materialize until a higher level of market penetration for the technology is achieved. Therefore, RVD systems at intersections, which are typically installed at least 17 feet above the road, remain one of the best alternatives to materialize the safety benefits of CV technology during a transition period.

1.1 Objectives

The objectives of the research project described were twofold. First, it evaluates an approach that can be used to communicate data from an RVD to CVs using BSM. In particular, it explores the feasibility of using RVD systems to supplement information available to CVs, including the communication of potential red-light-running vehicles that are non-CVs. Second, it evaluates the effectiveness of an advanced warning message (in the form of auditory and visual cues) in communicating the presence of a potential non-connected red-light-running vehicle crossing from a blind spot. This object was achieved by:

- creating an experiment in a driving simulator that exposes drivers to situations in which non-CVs are running a red light from a blind spot as shown in Figure 1.1, and
- collecting data about the reaction to the warning system from the participants of the experiment.

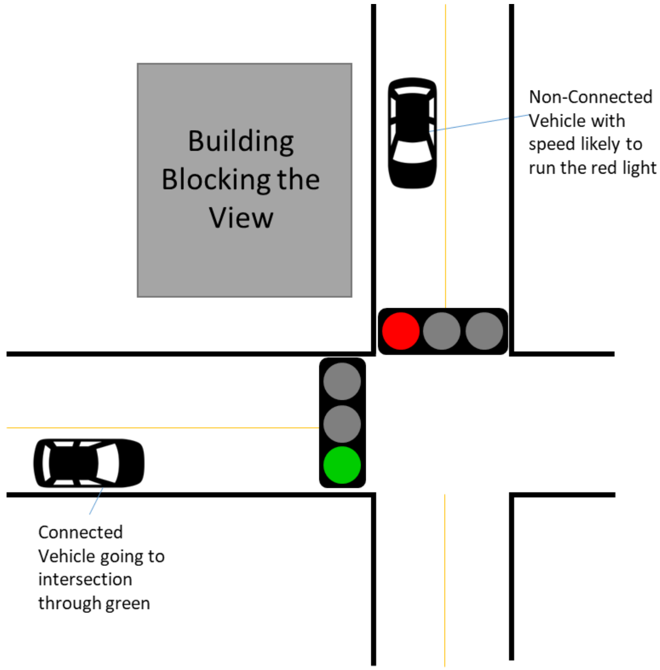

Figure 1.1 – Blind spot scenario example

1.2 Summary of Experimental Procedures

The driving simulator experiment will evaluate the effectiveness of a warning system that communicates the presence of a potential non-connected red-light-running vehicle to the driver. A visual warning message will be displayed as a head-up display (HUD) and will be followed by a simultaneous audio cue. Four different locations to trigger the warning system will be investigated: at the stop bar, 50 ft before the stop bar, 100 ft before the stop bar, and 150 ft before the stop bar. Subjects' reactions to the red-light-running vehicle will be recorded. Subjects will also be assigned a secondary task to keep them engaged while driving to emulate a real driving situation. Subjects will be asked to press the buttons on a clicker once they spot a pedestrian.

1.2.1 IRB Approval

The experimental and data collection procedures presented in this report were conducted after obtaining approval from the University of Wisconsin-Madison (UW-Madison) Social Sciences Institutional Review Board (IRB). The IRB also approved the public data-sharing procedures, which were included in the consent documents signed by the experiment participants. All members of the research team 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.

1.2.2 Summary of Results

The reaction time to the red-light-running vehicle was calculated from the moment the warning system was activated. The average reaction time for the warning system at the stop bar was 0.0515 sec. 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. Statistical tests showed a statistically significant difference in the mean of the reaction time between the different groups. Similar results were observed 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. Drivers reacted differently to the warning system, and some of them came to a complete stop. Subjects came to a complete stop for 29.73%, 17.5%, 29.27% and 47.7% of the events at the stop bar and 50, 100, and 150 ft before the stop bar, respectively. For the secondary task, subjects were able to detect 70.38% of the pedestrians, meaning that subjects focused more on driving and paid attention to pedestrians when necessary.

1.3 Report Structure

This report consists of seven sections and references. Section 1 includes an introduction to the research project along with the objectives of the research. Section 2 is a literature review consisting of elements from previous research on areas relevant to the objectives of this research. Section 3 includes a feasibility analysis. Section 4 describes the experimental procedures used to complete this analysis and defines and explains various characteristics of the apparatus and research test scenarios. Section 5 describes the experimental design and tasks along with the characteristics of the collected data. Section 6 provides the statistical analysis and the results of the research, and Section 7 presents conclusions and recommendations for future research. Finally, the references used in this research are presented at the end of the report.

2 Literature Review

In recent decades, humans have relied on vehicles as their main mode of transportation. Driving has become omnipresent. However, driving is a complex task that requires full attention and awareness. Several vehicles are now equipped with driving aids or advanced driver-assistance systems. 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. These systems include pedestrian-collision-warning systems, in-vehicle collision avoidance warning systems, and full-windshield HUD systems. These advances can also make promising technologies available to improve the safety of our transportation system. Existing literature relevant to the areas of drivers, red-light runners, and in-vehicle technology will be discussed in this section.

2.1 Driver Behavior

Drivers interact with other vehicles, pedestrians, and hazard objects. It is important to understand driver behavior to provide insights to better design of CVs. Identifying features of driving behavior can effectively lead to safer driving.

Driving requires the processing of a large amount of information related to the roadway and the surrounding environment under time and pressure constraints. The driving task is classified into three levels: control, guidance, and navigation. These levels differ based on complexity and safety, with navigation being the most complex and least safe level [1]. Driver attention is a key element of driving. Attention is defined as the ability to focus on certain objects and allocate processing resources accordingly [2]. Distraction is defined as the lack of attention. Concerns about distracted driving have gained national attention [3, 4] since it has been identified as one of the major causes leading to crashes [5]. With the advancement of in-vehicle technologies, drivers became more distracted and crashes increased [5]. Many of the embedded features of in-vehicle technologies are complex and require drivers to take their eyes off the road to understand them.

Drivers are prone to making mistakes because 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 [6, 7]. Around 40% of motor vehicle crashes in the US occur at intersections [8]. 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 [8–10].

2.2 Red-Light Runners

One of the major hazards to road safety is drivers disobeying traffic signals at signalized intersections. Studies have shown that a high percentage of severe road crashes occur at intersections and that a high percentage of these crashes are due to drivers disobeying or "running" the red light [11]. Red-light violation has high rates at busy urban intersections, and the highest rates have been recorded during peak hours. Red-light running 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 [12].

Retting and Williams [13] assessed the characteristics of red-light runners. The study reported two red-light runners per hour in a total of 234 hours of data collection. The results concluded that the red-light runners are drivers under the age of thirty years, have poor driving history, are likely to use seat belts, and drive small and older cars. In their study, Retting et al. [10] reported red-light violations at the rate of 5.2 runners per hour on a divided, six-lane, 45 mph principal arterial and 1.3 runners per hour on a four-lane, 30 mph roadway. Porter and England [14] reported that unbuckled and non-Caucasian drivers are more likely to run and violate red lights. Mane and Pulugurtha [15] summarized factors leading to red-light-running behavior and red-light crashes from past studies. All-red clearance time, yellow change time, and traffic volume were the main contributing factors.

With the advancement of technology, algorithms have been developed and integrated to detect red-light runners. However, the number of red-light crashes is still high. One way to reduce such crashes is to rely on infrastructure and CVs. In-vehicle sensors should be able to detect a potential red-light runner and communicate this information to the driver.

2.3 In-Vehicle Technologies

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 [16–20].

Head-down displays are located in the middle of the control panel of the vehicle. While an HDD is useful in navigation, drivers must take their eyes off the road so they can read this display while driving. Hence, they present a possibly serious problem when it comes to driver distraction [16].

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 [16]. Continental, one of the leading manufacturers of HUD, is supplying vehicles such as BMW, Mercedes Benz, and Audi with HUD [17]. 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 [13,14,15].

Augmented reality display is a more advanced form of HUD. It is currently the most advanced technology on the market and is being tested in luxury car brands. An AR display can project lane departure warnings, automated cruise control, and blind-spot monitoring augmented on the road itself. For example, if the driver is deviating from the lane, the vehicle will produce visual, audible, and haptic alerts to warn the driver about the situation he is facing. Other examples include projecting a virtual arrow on the road itself for better navigation or illuminating the roadway at night [17].

Head-up displays and AR displays reduce driver distraction and increase driver safety. They display the necessary information when needed. In-vehicle technology represents a key element in the human-machine interface.

2.4 Testing In-Vehicle Technologies

In-vehicle technology has grown over time and continues to improve. Several studies have examined the effectiveness of in-vehicle systems. One main challenge with in-vehicle systems is avoiding distraction and attention deficits while driving. Studies have used driving simulators and real traffic driving to evaluate in-vehicle systems. Studies have shown that in-vehicle systems can increase safety while driving if driver-system interaction did not impact visual demands [21].

A study [22] conducted by the Minnesota Department of Transportation showed that drivers followed speed limits when supplemental information from in-vehicle systems was presented. The study also showed that in-vehicle systems information reduced drivers' workload and helped drivers in unfamiliar environments. Using a full-windshield HUD system, Wu et al. [23] detected and highlighted road signs. Drivers were able to navigate complex driving situations more easily. Augmented reality displays were shown to help drivers in situations that required dividing attention between several tasks [24]. They were also shown to help cognitively impaired older drivers and improve their safety [25], as well as to help drivers detect hazardous objects faster [26]. In addition, AR cues and AR-HUD allowed drivers to make safe left turns without distracting drivers [27, 28].

The driving simulator can be used to explore a variety of in-vehicle technologies before their implementation. The interaction between drivers and such technologies can be studied, improved, and then implemented.

2.5 Literature Review Summary

Advanced in-vehicle technologies present great potential in offering information such as navigation, logistics, and safety measures to drivers at the needed time. Head-up and AR displays are currently the most used technology on the market. These displays help direct the drivers' attention to the road and improve their response time to hazards. The literature review also looked at the behavior of drivers. Drivers disobeying traffic signals at signalized intersection pose a safety risk to themselves and their surroundings. However, there remains a gap in the research when it comes to assessing in-vehicle technology related to red-light runners. There exists an opportunity to explore the use of advanced in-vehicle systems to mitigate the effects of red-light runners.

3 Feasibility Analysis

One of the objectives of this project calls for exploring the feasibility of using RVD systems to supplement information available to CVs, including the communication of potential red-light-running vehicles that are non-CVs. As previously mentioned, due to the limited proliferation of CVs, such applications will have little value until a larger number of vehicles can be connected. Rather than waiting for every potential red-light runner to purchase a CV vehicle or system, RVD allows non-CVs to provide CV-like messages via the infrastructure to all CVs in a range near the intersection.

Radar-based vehicle detection is one of the most significantly underused components of the transportation system infrastructure. These detection systems are typically installed at signalized intersections to monitor the presence of vehicles within a predefined zone but have the capability of continuously tracking the position and speed of vehicles approaching an intersection. Position and speed are two of the major components of the CV BSM. Thus, through a software-based approach, RVD systems can be used to mimic a CV and send non-CV information to CVs. This expands the capabilities of RVD systems to address operational and safety problems not possible with existing approaches that focus on traditional countermeasures.

Figure 3.1 – Detection systems at a signalized intersection

To test the messaging communication between the traffic signal's roadside equipment (RSE) and the vehicle's onboard equipment (OBE), the following steps were taken.

- An on-board unit (OBU) was installed in a demonstration vehicle.
- On-board equipment, including a tablet equipped with vehicle-to infrastructure messaging software, was installed on the demonstration vehicle.
- The demonstration vehicle was driven through the intersection in all three crossing paths to verify signal phase and timing (SPaT), and BSMs were received and transmitted.

The results of this test are shown in Figure 3.2, Figure 3.3 and Figure 3.4.

- In Figure 3.2, the MAP message is shown (lanes in blue), along with the signal heads with their current phases and the location of the demo vehicle.
- Figure 3.3 shows the vehicle's BSM pinpointing the precise location of the vehicle as shown in Figure 3.2 . The vehicle was parked facing almost due north.
- Figure 3.4 shows the HUD for the current signal phase based on the processing of SPaT messages received from the RSE at the intersection. Shown here is a red signal head showing time until phase change to a green signal.

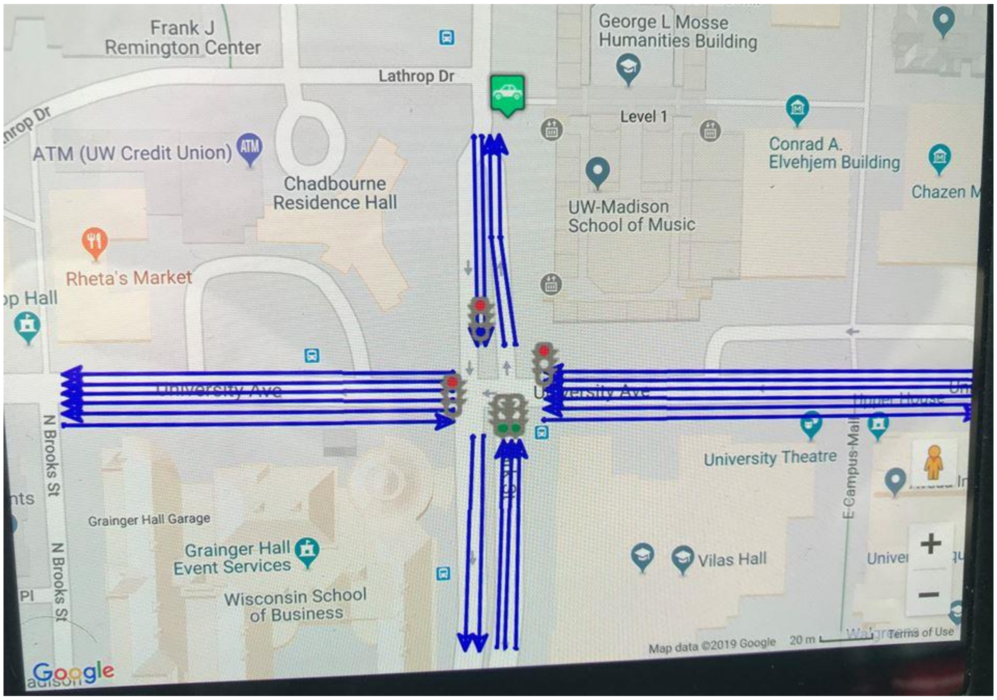

Figure 3.2 – Image of the on-board tablet showing MAP, signal phases, and vehicle location

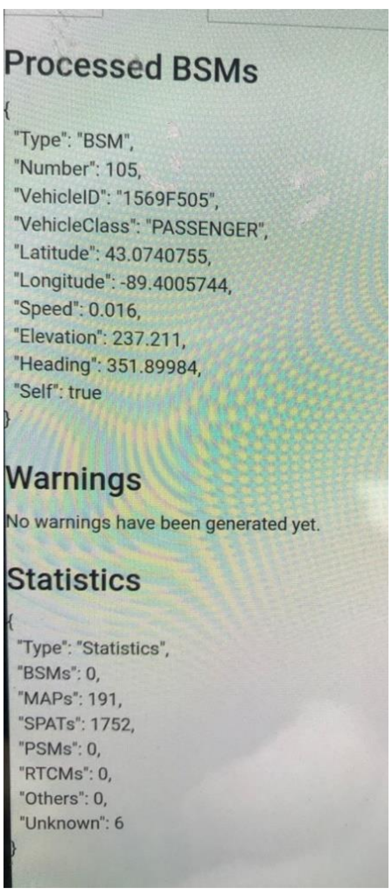

Figure 3.3 – Vehicle's BSM message

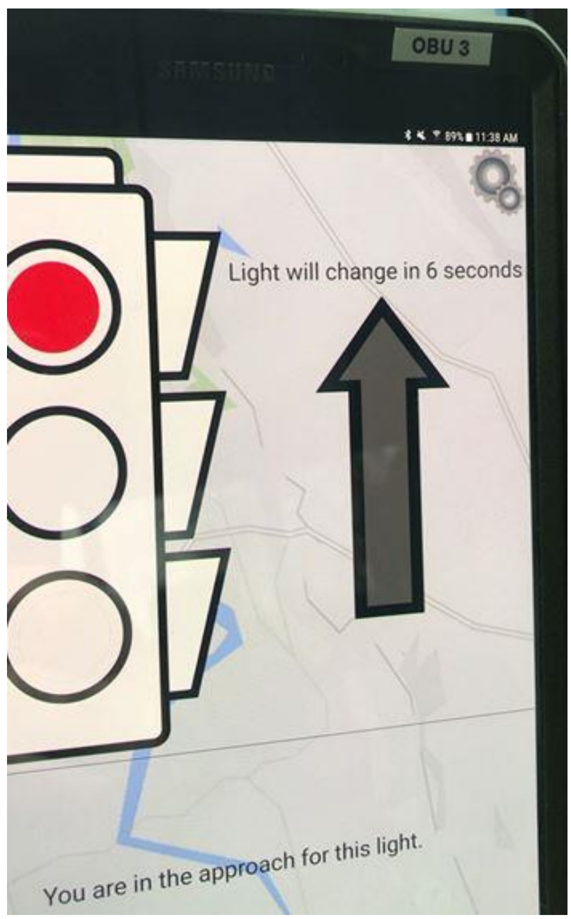

Figure 3.4 – SPaT interface showing signal phase and progression

The specific flow of information is shown in Figure 3.5 and Figure 3.6. Specifically, Figure 3.5 shows the scenario where a non-CV would communicate to a CV via the intersection infrastructure. Figure 3.6 shows the flow of information.

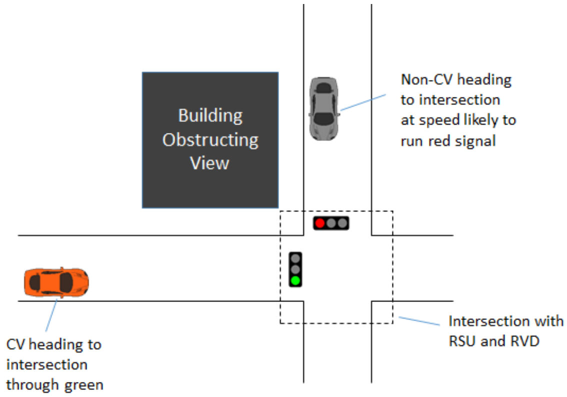

Figure 3.5 – Example "blind" scenario

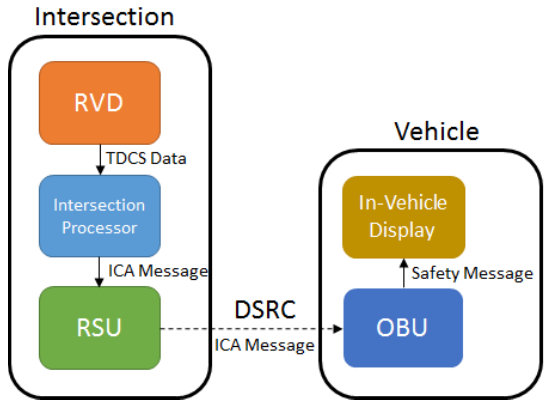

Figure 3.6 – System design for project

The steps of information flow are:

1. Non-CV first detected by RVD at the intersection.
2. Non-CV location, speed, and heading monitored by RVD (trajectories data collection system (TDCS) data).
3. The intersection processor receives the TDCS messages as well as current signal phases.
4. An algorithm running on the interaction processor determines if the vehicle is in a state where the red-light signal is likely to be violated.
5. An intersection collision avoidance (ICA) message is developed and provided to the roadside unit (RSU) for transmission.
6. The RSU transmits a MessageFrame message (including the ICA message) to OBUs in range.
7. The CV OBU picks up the MessageFrame message.
8. The ICA message is processed in tandem with the CV's position, speed, and heading on the OBU processor to determine if a safety message should be communicated to the driver.
9. The safety message is provided to the driver.

Note that Steps 6-9 are completed for a true ICA message that was developed by a CV and should be handled identically to that situation. Steps 1-5 replace a typical BSM provided by a CV via the OBU to an RSU. Thus, the only additional software required to be developed is at the intersection processor to determine and create the ICA message from TDCS data.

3.1 Intersection Collision Avoidance (ICA) Message

The following statement is produced verbatim from the SAE J2735 MAR2016 message set.

This message is intended to be used to broadcast to other DSRC devices in the area a warning of a potential collision with a vehicle that is likely to be entering an intersection without the right of way. This sender may be either an equipped vehicle or another source such as the infrastructure.

The message includes the many components and subcomponents outlined in Figure 3.7. For the mapping of the TDCS data to this message, only some of the optional components will be included. Figure 3.8 shows which elements will be used, with those unused grayed out. The TDCS message format is included in Figure 3.9.

A temporary vehicle identifier is directly mapped from the VehicleID field of the TDCS data. Message count, intersection ID, event flag, time, and Global Navigation Satellite System (GNSS) status are also set by the intersection processor.

Information on vehicle position (latitude/longitude), heading, lane or approach, and speed is derived from the TDCS messages and algorithm. Historical values are included based on previous ICA messages. Historical elevation is required in the path history element but will be set to -1 and not used.

Complete TDCS-to-ICA mapping is shown below in Table 3.1.

Table 3.1. Complete ICA message mapping information from TDCS and intersection processor

ICA Message Parameter	Data Source
Message Count	0 to 256, then resets
Temporary Vehicle ID	VehicleID
Intersection ID	Defined by research team for given intersection
Lane or Approach ID	Approach
Event Flag	If event, set to "Intersection Violation"
GNSS Status	Based on current availability of GNSS
Time: Year	Current year
Time: Month	Current month
Time: Day	Current day
Time: Hour	Current hour
Time: Minute	Current minute
Time: Second	Current second
Time: Zone	Current time zone
Longitude	XCoord and YCoord
Latitude	XCoord and YCoord
Heading	Null for first value, then derived based on lat/lon offset
Speed	Speed
Path History: Latitude Offset	Delta latitude from previous measure
Path History: Longitude Offset	Delta longitude from previous measure
Path History: Elevation Offset	-1 (unused, but required in ICA message)
Path History: Time Offset	Delta t from last measure, should be 0.1 seconds
Path History: Speed	Previous speed value
Path History: Course Heading	Derived based on lat/lon offset

Legend
Set by intersection processor software
Direct from TDCS data
Derived from TDCS data

Currently unused TDCS data includes vehicle length, vehicle summary (history) information (as this is stored in the ICA message), anchor time, file length, and error messages.

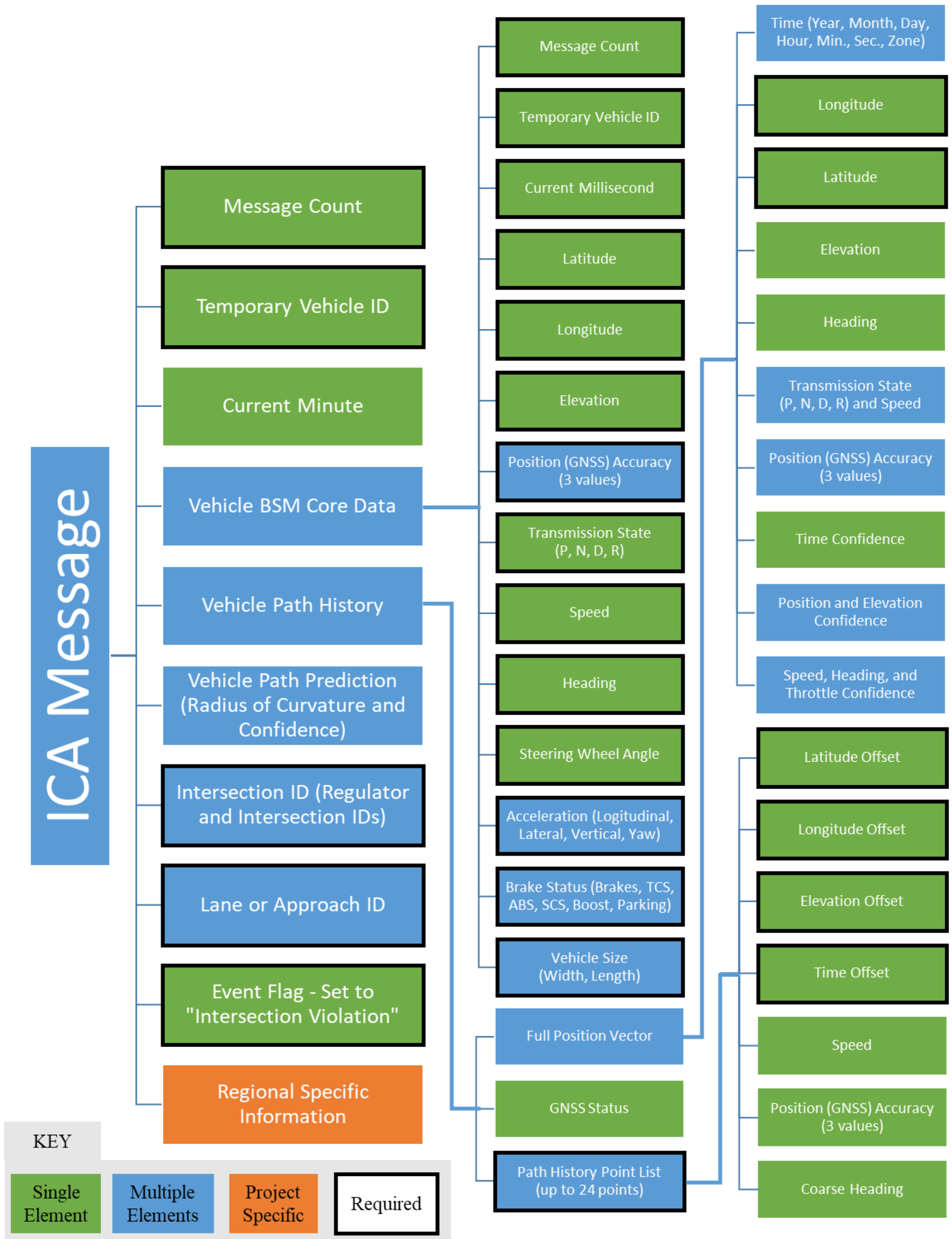

Figure 3.7 – ICA message format

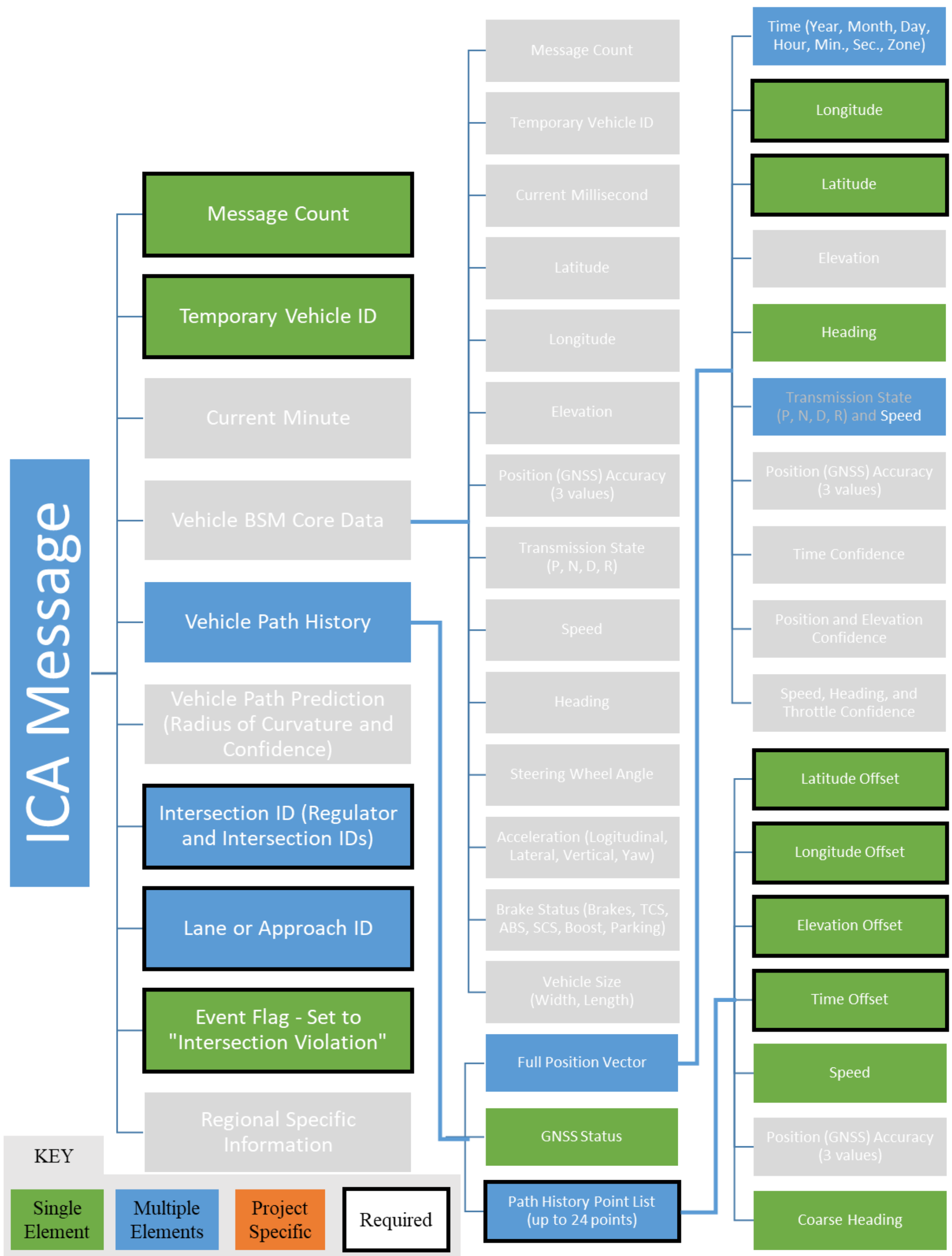

Figure 3.8 – ICA message components used

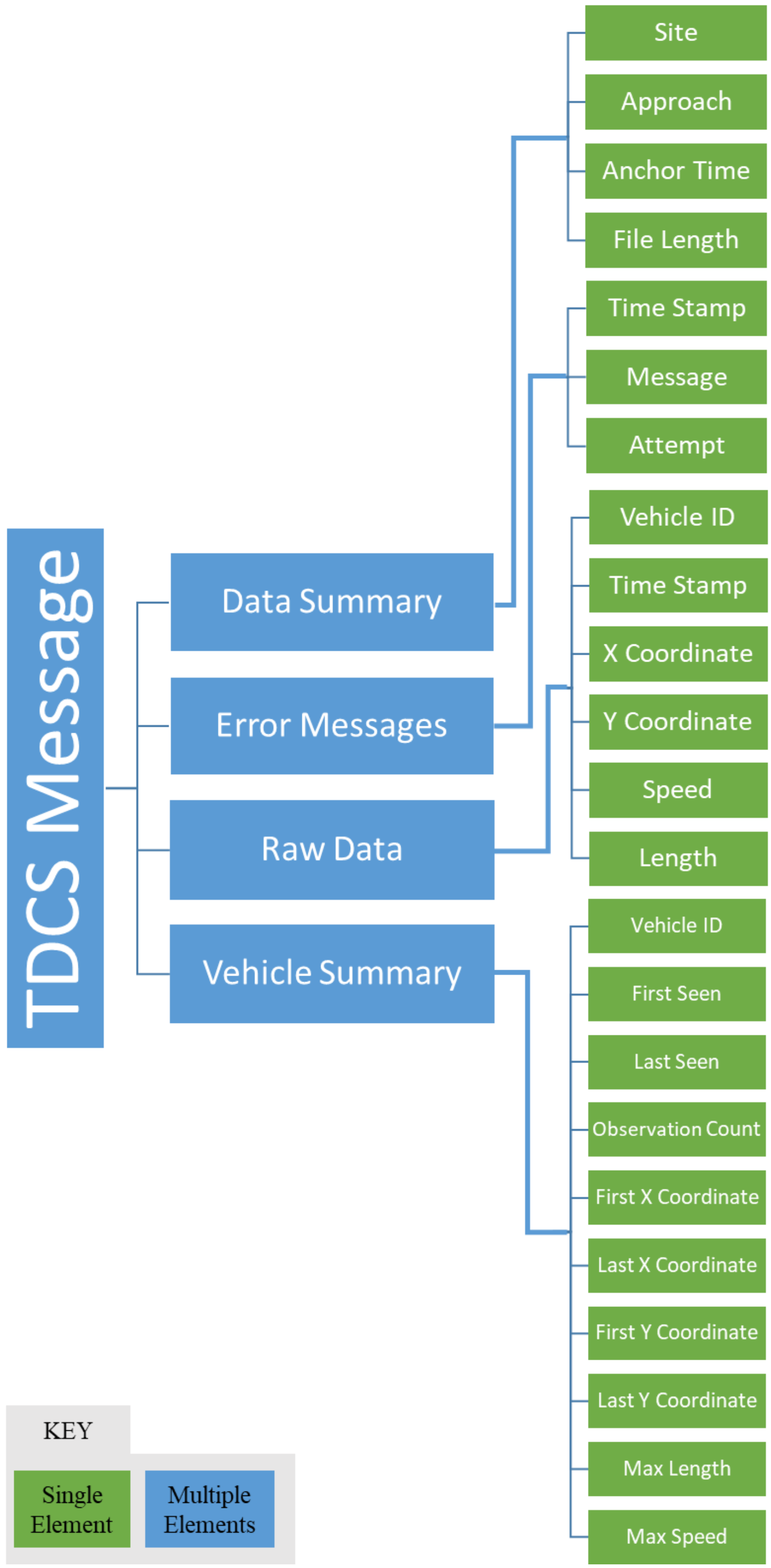

Figure 3.9 – TDCS Message Format

4 Scenario and Experimental Procedures

Experimental procedures described in this report were conducted on a full-scale, state-of-the-art, Ford Fusion driving simulator located at UW-Madison, shown in Figure 4.1. The sections ahead present the characteristics of the driving simulator. Recruited subjects drove a virtual world in the simulator, and driving behavior was analyzed from data produced by the simulator. Subjects were exposed to driving conditions designed to achieve the previously defined objectives of the project. The following sections discuss the consent process that subjects went through prior to participating in the experiment and the characteristics of the virtual world to which subjects were exposed.

Figure 4.1 – Full-scale driving simulator at UW-Madison

4.1 UW-Madison Driving Simulator

Experiment participants (subjects) can interact with the UW-Madison full-scale simulator shown in Figure 4.1 and drive it as if they were driving a real car. As stated previously, the simulator can project a virtual world in which subjects can interact with the virtual roadway environment as if they were on a real roadway. 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. For the experiment described in this report, the research team relied on an additional instrumentation approach to collect responses from subjects. This approach involved the use of a push button. The supplemental instrumentation used is described in Section 5.4.

4.2 Subject Consent Process

Before participating in the experiment, subjects were first shown the driving simulator and given an overview of how the system operates. Subjects who decided to participate in the experiment were then asked to read and sign a consent form. After signing the consent, subjects drove a practice session in the simulator and then proceeded to participate in the experiment. During the introduction to the process, subjects were reminded several times that they could stop the simulation by pressing an emergency push button located near the gear shifter and that they could withdraw from the experiment at any time. The following sections provide additional details about the consent process and the practice sessions. Details about recruited subjects for the experiment are described in Section 5.2. All subjects had a valid driver's license.

4.2.1 Consent Process

The study was explained to subjects through written informed consent. The consent process gave subjects adequate information about the study, responded to any questions they asked, and ensured that subjects understood the information conveyed. The research team kept a signed copy of the consent form, while a copy of the consent form containing contact information was given to the subjects in case they had questions about the study.

4.2.2 Practice Session after Consent

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

4.3 Scenario for Experiment

The scenario of the experiment was designed based on the objectives of the experiment. Limitations of the simulation experiments, such as how long subjects can drive in a simulation environment, were taken into account. The sections ahead describe the specific goals of the scenario and the geometric characteristics of the roadway alignment of the scenario.

4.3.1 Experimental Goals

The primary goal of the experiment was 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 used to communicate the presence of a non-connected red-light-running vehicle was a combination of visual and auditory cues that were triggered during the experiment based on a pre-defined experimental matrix. The visual message was displayed as a HUD.

The full-scale driving simulator experiment involved situations in which a non-CV runs the red light. Subjects were asked to drive as they would normally and were not told about red-light runners' events. Their reactions to the red-light-running vehicle were recorded.

4.3.2 Geometric Characteristics

The scenario involved an urban roadways cross-section. Driving was conducted with the simulator set to emulate normal weather conditions (day driving, good visibility, no rain or snow). The drive was 3888 meters (2.4 miles) long. Figure 4.2 shows a continuous urban cross section that aims to reduce simulation sickness. The scenario drive was split into 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 24 sec, respectively. Figure 4.3 shows the scenario drive for each run.

Figure 4.2 – Urban roadways cross section

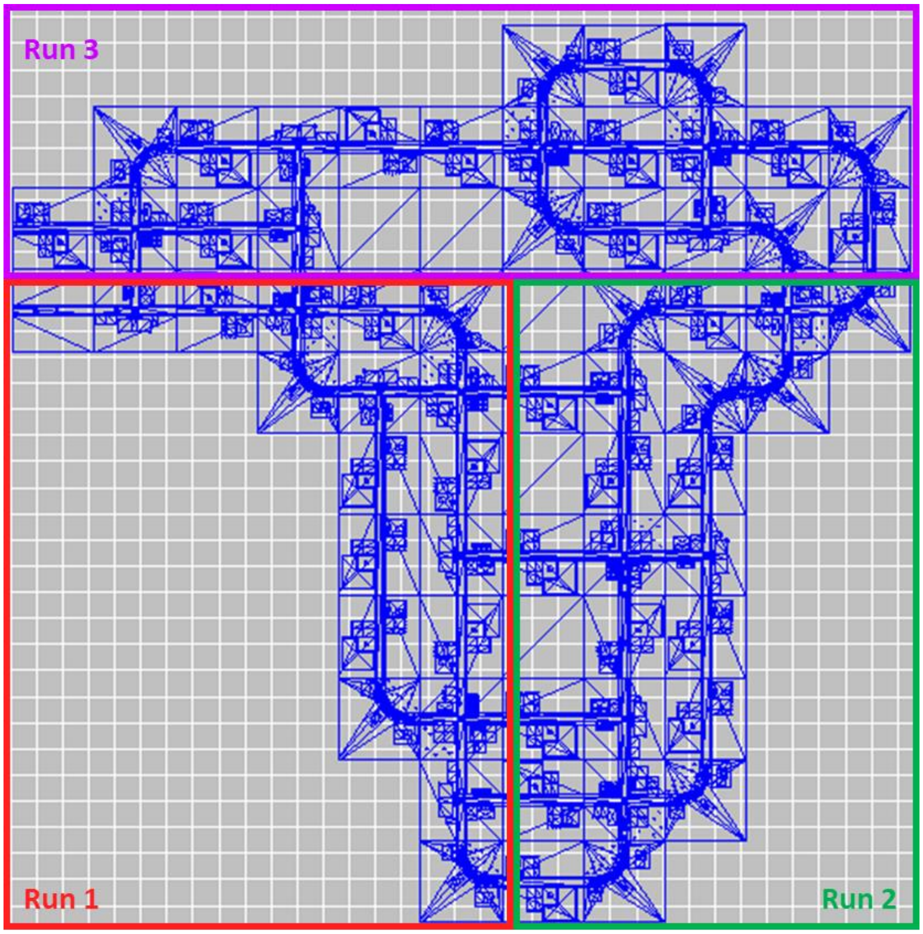

Figure 4.3 – Scenario drive for each run

5 Experimental Design and Data Collection Procedures

5.1 Experiment Tasks

As previously mentioned, the experiment involved subjects driving through an urban virtual world. Subjects were asked to follow the main road without making any turns. While driving, subjects encountered vehicles running a red light, and they reacted accordingly. For the duration of the experiment, subjects were assigned a secondary task to keep them engaged while driving to emulate a real driving situation. The secondary task was a roadside visual detection task, which was defined by pressing the buttons on a clicker once they spotted a pedestrian. In total, subjects had to react to 9 non-CVs running the red light. They also had to click 13 times for the secondary task involving a pedestrian.

5.2 Subject Characteristics

The experimental plan used to develop the experimental matrix discussed in Section 5.3 was based on 20 subjects. Subjects recruited were an average of 32 years old (ranging from 19 to 75 years of age), with 10 males and 10 females. All subjects were licensed drivers with between 1 and 52 years of driving experience. All had normal or corrected-to-normal vision.

5.3 Experimental Matrix

In the experiment, participants were exposed to an imminent collision scenario with a red-light-running vehicle. Several versions of the same scenario were created to accommodate the requirements of an experimental matrix designed to randomize the location of the cue to which subjects were exposed.

Participants in the control group received a warning about the potential red-light-running vehicle at the stop bar. Participants in the treatment group received a warning message displayed on as a HUD at a distance of 50 ft, 100 ft, or 150 ft from the stop bar. The warning message was accompanied by an auditory warning. Figure 5.1 shows the visual warning message displayed on the windshield as a HUD.

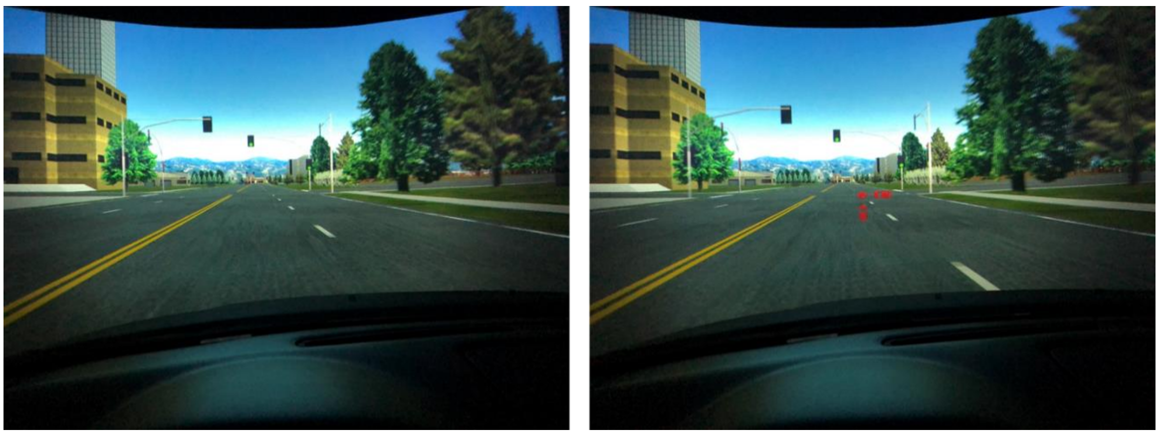

Figure 5.1 – No alert displayed (left) versus alert displayed (right) as a HUD

As a result of the experimental design and the number of subjects for the experiment, a total of 180 red-light-running events were identified. The events were distributed evenly in the control and treatment groups. One-quarter of the subjects was randomly placed in the control group and received a warning about the potential red-light-running vehicle displayed as a HUD at the stop bar. One-quarter of the subjects were placed in the treatment group and received a warning about the potential red-light-running vehicle displayed as a HUD at a distance of 50 ft. from the stop bar. Another quarter of the subjects received the warning message at a distance of 100 ft. from the stop bar. The remaining quarter of the subjects received the warning message at a distance of 150 ft. from the stop bar. Figure 5.2 shows the distribution of participants for each event.

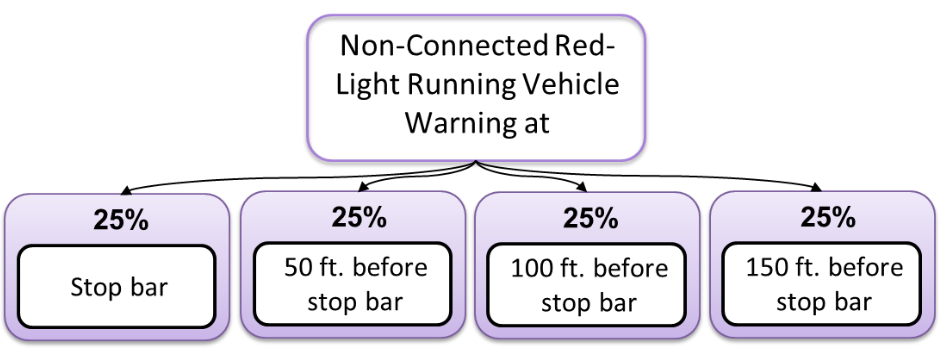

Figure 5.2 – Participant distribution

5.4 Subject Response for Secondary Task

In addition to collecting vehicle performance data obtained from the driving simulation experiment, subjects were asked, as a secondary task, to press the button on a clicker when they saw a pedestrian. A photo of the device (a Bluetooth button) used to collect the response is shown in Figure 5.3.

Figure 5.3 – Push button

5.5 Additional Data Collected

In addition to the clicker response data previously mentioned, typical vehicle performance data (speed, position, and time) were collected as part of the experiment. Additionally, video recordings of the experiment were used to simplify the data analysis process presented in Chapter 6. Neither the subject's face nor voice was recorded.

6 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. Video recordings obtained during the experiments were used to confirm the results and the observations. Throughout the analysis process, collected data were visually and statistically inspected to identify outliers.

6.1 Summary of Data Collected

Twenty subjects were recruited to participate in the experiment. None of the subjects had simulation sickness during the practice session. However, the oldest driver (75 years old) dropped out after driving 1 min 20 sec of the first run due to simulation sickness concerns. Also, the youngest driver (19 years old) dropped out after completing the first run due to simulation sickness concerns. Another participant dropped out after completing the first run, and two other participants dropped out after completing two runs due to simulation sickness concerns. As a result, a total of 154 experimental data is available for analysis from the 20 subjects. The sections ahead provide a summary of the data collected from the driving simulator.

6.1.1 Location of Response to Red-Light-Running Vehicles

Each driver reacted differently when exposed to an imminent collision scenario with a red-light-running vehicle. Figure 6.1 shows the location of the reaction from the stop bar while approaching the events with a red-light-running vehicle. Figure 6.2 and Figure 6.3 show the location of the reaction from the stop bar while approaching the events with a red-light-running vehicle traveling westbound and eastbound, respectively.

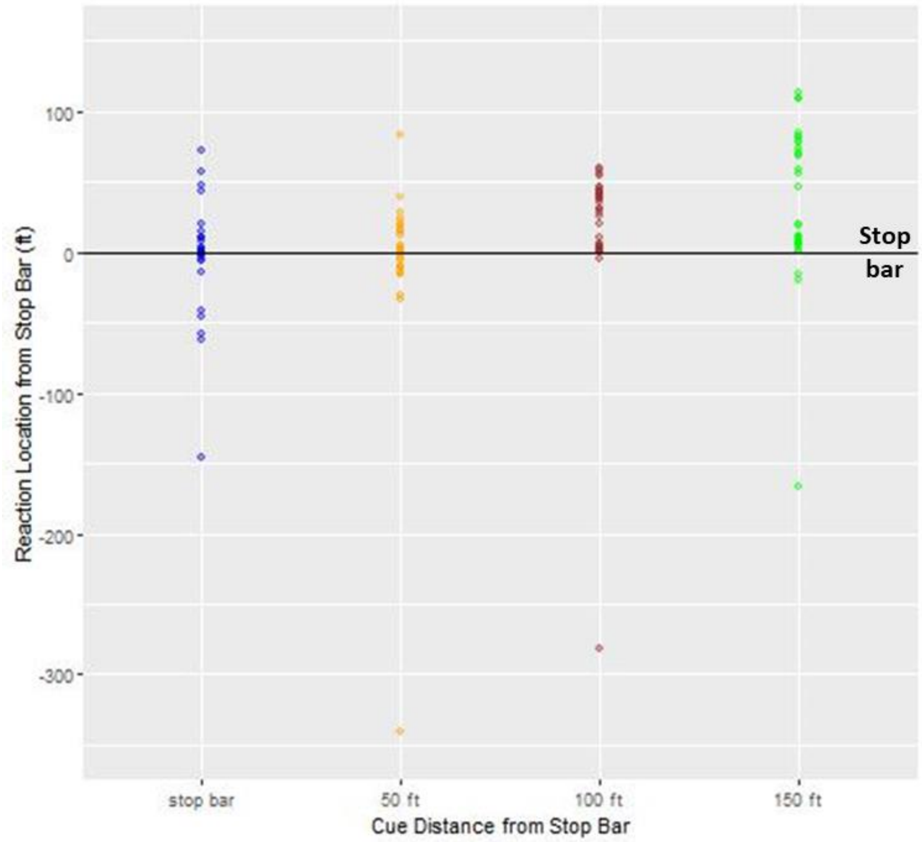

Figure 6.1 – Location of response to the red-light-running vehicle from the stop bar

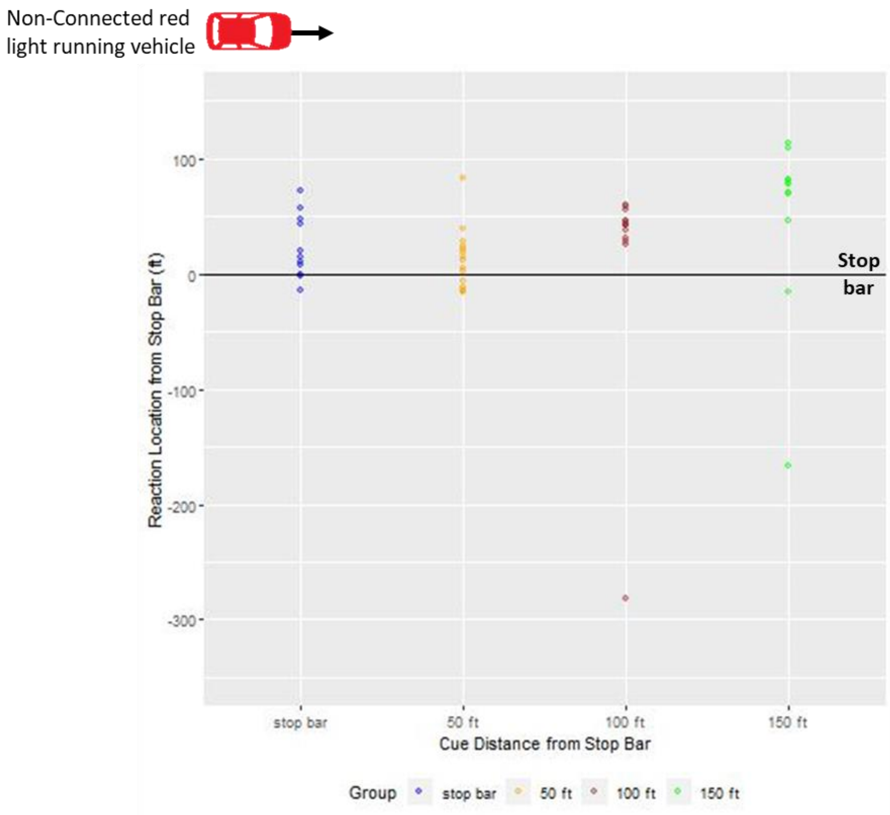

Figure 6.2 – Location of response to the red-light-running vehicle traveling eastbound from the stop bar

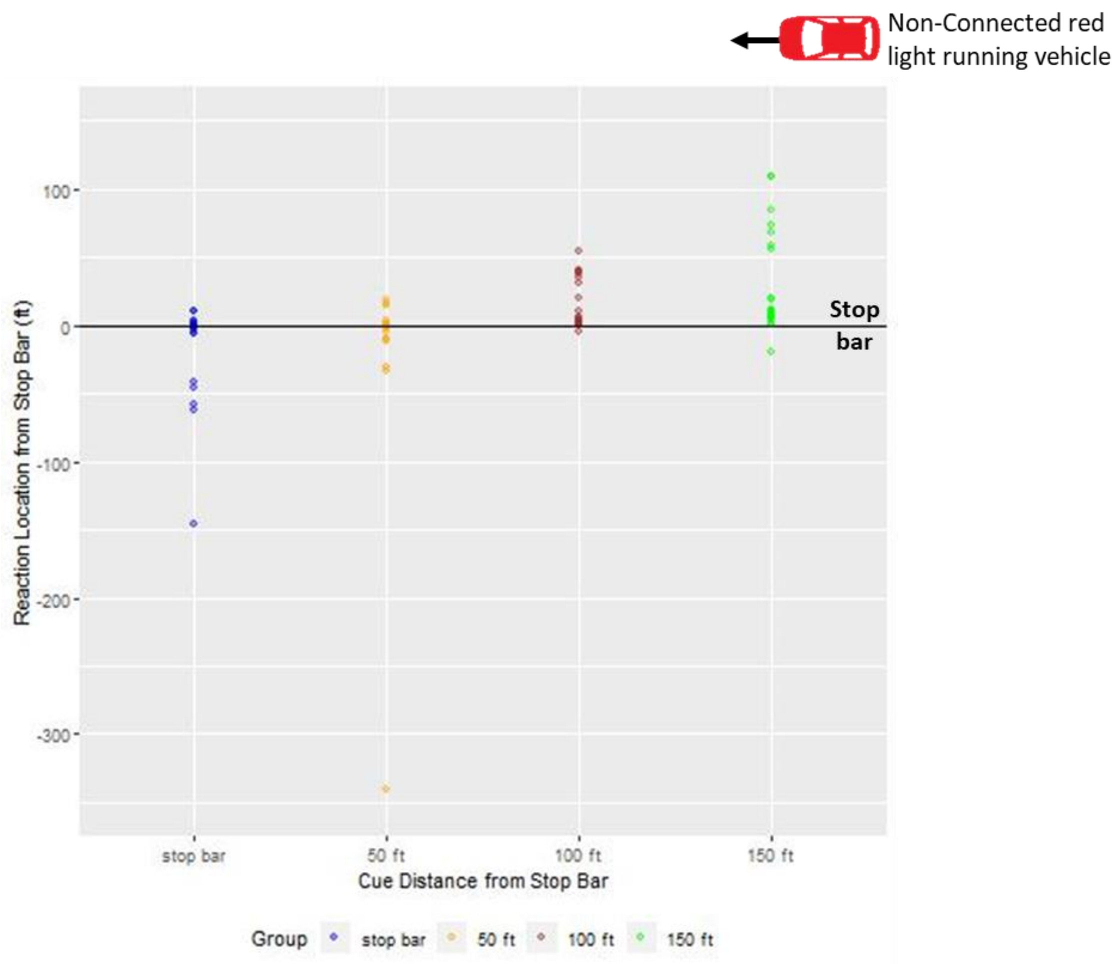

Figure 6.3 – Location of response to the red-light-running vehicle traveling westbound from the stop bar

6.1.2 Available Data 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 pedestrian as a secondary task is also available.

6.1.3 Principles Used in Data Analysis

For each subject, data were visually inspected to remove anomalous performance measures. This is due to subjects driving way below the speed limit. A slow driving behavior did not lead to an imminent collision scenario with the red-light-running vehicle, and the warning system was not activated as designed for the purpose of this research.

The median absolute deviation (MAD) was then used as the statistical filtering method to identify outliers. It is defined as follows:

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

where x_i is the individual observation and $\tilde{x}$ is the median of the datasets. A MAD value is calculated for each reaction time in the data set as the absolute difference between the reaction time and the median of all reaction times. 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.

6.1.4 Statistical Tests Used

A normal or Gaussian distribution dataset is required for statistical tests, such as the t-test, analysis of variance (ANOVA), and regression. Since the validity of such tests depends on the distribution of the data, these types of tests are called parametric tests. Before the use of parametric tests, normality and other test assumptions should be evaluated to draw reliable interpretations. Non-parametric tests are used instead of the parametric test in situations where the normality assumption is violated. Hence, before starting the analysis, the collected data were inspected for normality to determine the appropriate test to use by performing preliminary tests.

Density plots and quantile-quantile plots (Q-Q plots) were generated for each analysis category to visually inspect the normality of the dataset. In addition to visual inspection, the Shapiro-Wilk test was used to compare the sample distribution to a normal distribution in order to determine whether or not the data deviates from a normal distribution.

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

6.2 Speed Profiles

Speed profiles were plotted for each subject. In addition to the driver's speed, the moment an alert was displayed was shown on the same speed profile. An example of such a profile is shown in Figure 6.4. Subjects saw the red-light-running vehicle and reacted to it before the warning system activation at the stop bar as displayed in the left image. Although the red-light-running vehicle crossed from a blind spot, it became visible to the driver around the stop bar area. Hence the warning system activation was not faster than the visibility zone of the driver. On the other hand, the right image shows the activation of the warning system 30 ft before the stop bar. The driver 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 runner cleared the intersection.

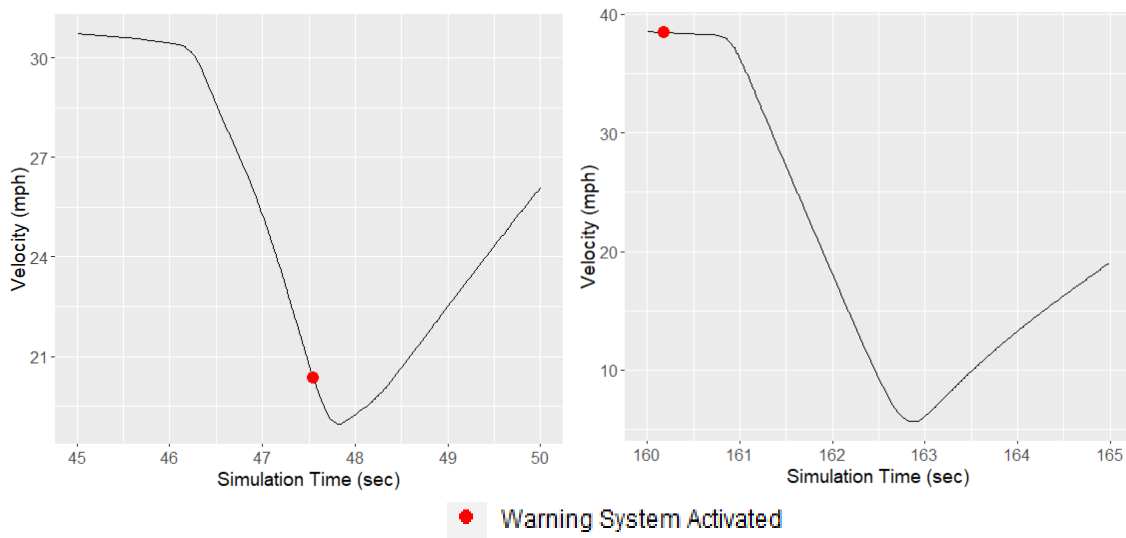

Figure 6.4 – Speed profile example with warning system activation moment: at a stop bar(left) and at 30 ft before the stop bar (right)

6.3 Results of Reaction-Time-Based Analysis

The dataset was analyzed as a whole set, and the control group was compared against the three different locations of the warning system. In addition, the data was split into two categories based on the direction traveled by the red-light-running vehicle. Similar comparisons were conducted for each category. To visualize the data, a box plot and a density plot that summarize the data were used for each group and category.

6.3.1 Reaction-Time-Based Analysis for All Data

A density plot and a box plot are shown in Figure 6.5 and Figure 6.6 to visually summarize the data for each group. The plots are a representation of the data after filtering the outliers. The reaction time to the red-light-running vehicle was calculated from the moment the warning system was activated. The average reaction time for events with a warning system at the stop bar was 0.0515 sec. Most drivers saw and reacted to the red-light-running vehicle before the activation of the warning system, which led to negative reaction time. The average reaction times for events with warning systems 50 ft, 100 ft, and 150 ft before the stop bar were 0.942 sec, 1.22 sec, and 1.31 sec, respectively.

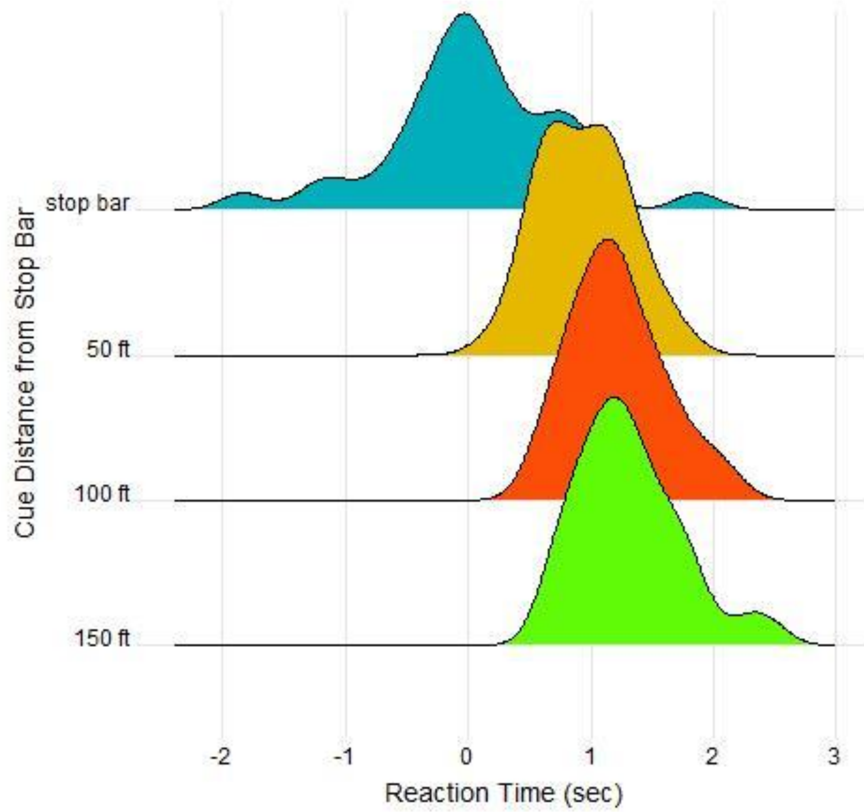

Figure 6.5 – Density plot per warning system group

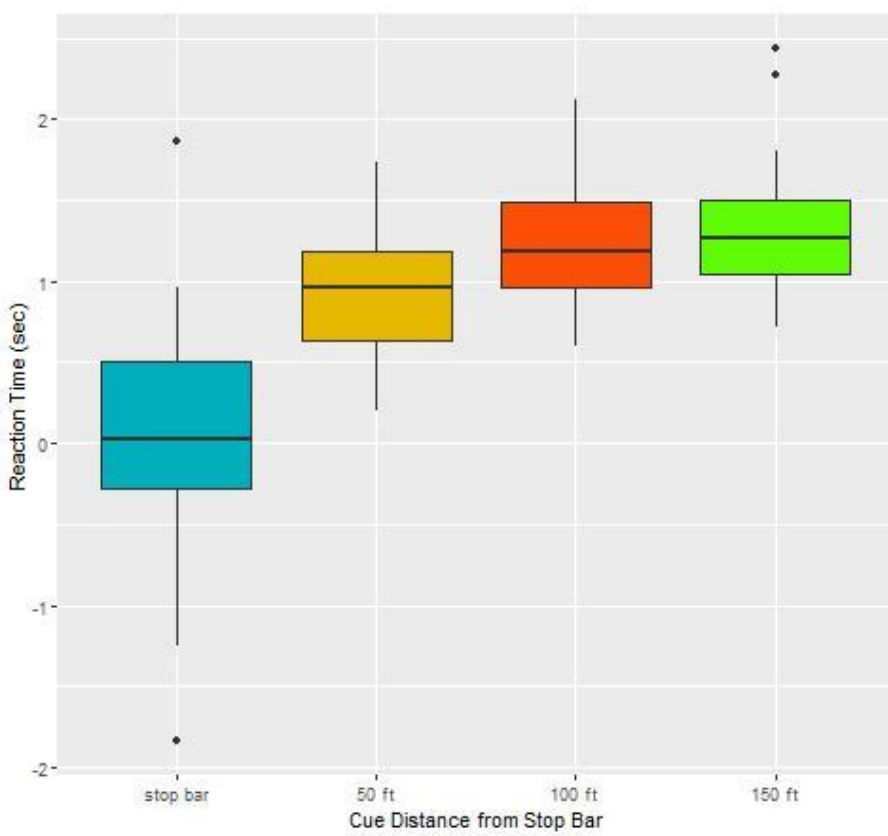

Figure 6.6 – Box plot per warning system group

For each group, selected summary statistics are shown in Table 6.1. These values are for the whole dataset after removing outliers.

Table 6.1 – 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			

The Kruskal-Wallis test was used to compare the reaction time means between the different locations at which the warning system was triggered. The results showed a p-value less than 0.05 (0.1 and 0.001), meaning that 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.

From the output of the Kruskal-Wallis test, a significant difference between groups exists. However, there is no indication of which pairs of groups are different. Multiple pairwise-comparison was then performed to determine if the mean difference between specific pairs is statistically significant. A pairwise Mann-Whitney Wilcoxon test was used to calculate pairwise comparisons between group levels with corrections for multiple testing, and the results are shown in Table 6.2. There is 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. In addition, there is 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.

Table 6.2 – 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

6.3.2 Reaction-Time-Based Analysis by Direction Traveled by the Red-Light-Running Vehicle

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 density plot and a box plot per direction traveled by the red-light-running vehicle are shown in Figure 6.7 and Figure 6.8 to visually summarize the data for each category. The average reaction time for events with a warning system at the stop bar and 50 ft, 100 ft, and 150 ft before the stop bar are summarized in Table 6.3.

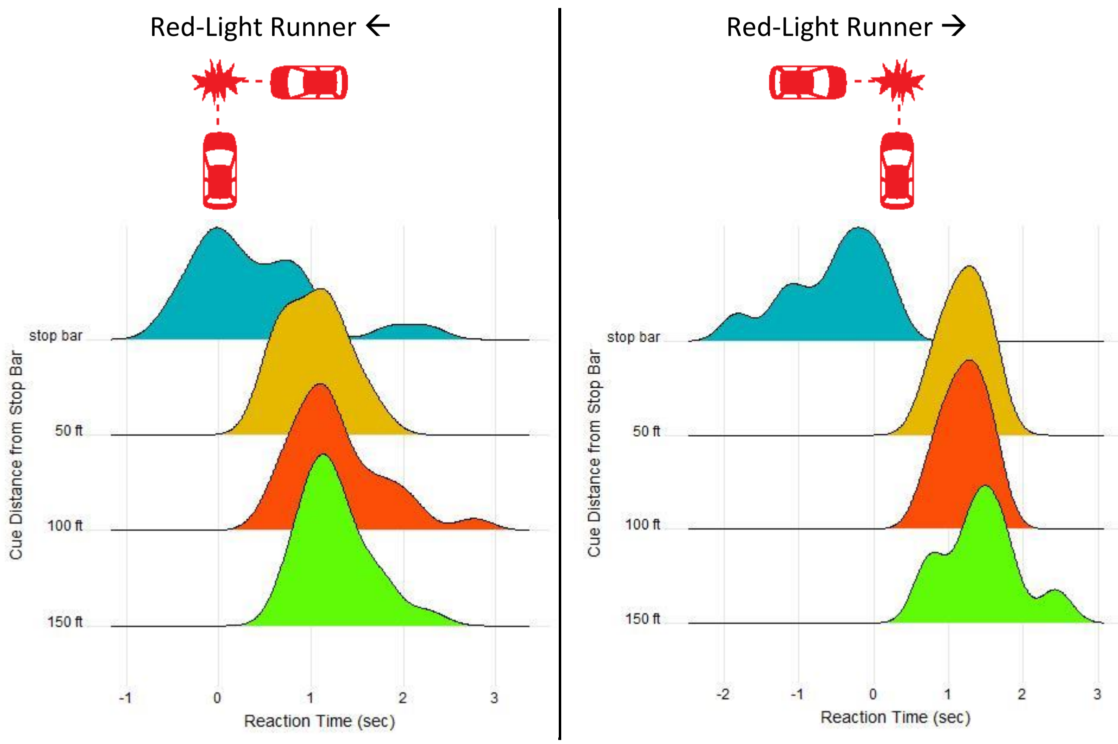

Figure 6.7 – Density plot per warning system group per direction traveled by the red-light-running vehicle

Figure 6.8 – Box plot per warning system group per direction traveled by the red-light-running vehicle

Table 6.3 – Summary statistics per direction traveled by the red-light-running vehicle

	Red-Light Runner ←				Red-Light Runner →			
								
	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 Kruskal-Wallis test was used to compare the reaction time means between the different locations at which the warning system was triggered. The results showed a p-value less than 0.05 (0.1 and 0.001) for each travel direction. This outcome means that 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.

Multiple pairwise comparison was then performed to determine if the mean difference between specific pairs is statistically significant. A pairwise Mann-Whitney Wilcoxon test was used to calculate pairwise comparisons between group levels with corrections for multiple testing, and the results are shown in Table 6.4. There is 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. However, there was no 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 for both directions of travel.

Table 6.4 – 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 ← 	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 → 	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

6.4 Descriptive Statistics Speed-Based Analysis

Looking at the speed profiles for the 20 subjects, drivers reduced their speed after seeing and hearing the warning alert. 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 at 50, 100, and 100 ft before the stop bar, respectively. For each location of the warning system, a summary of statistics is shown in Table 6.5. Drivers reacted differently to the warning system, and some of them came to a complete stop. Subjects 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, as shown in Table 6.6. Similar statistics are available for each travel direction of the red-light-running vehicle, and the results are shown in Table 6.7 and Table 6.8.

Table 6.5 – Speed reduction and duration of reduction (all data)

	Speed reduction (mph)				Duration of speed reduction (sec)			
	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
Minimum	0.85	0.43	1.02	0.67	0.48	0.42	0.98	1.63
Maximum	36.07	37.19	36.7	34.27	12.25	14.68	16.16	17.82
Average	16.17	15.47	16.86	21.62	2.15	2.24	2.59	3.15
Standard Deviation	10.67	8.99	11.28	8.62	1.86	2.30	2.28	2.87

Table 6.6 – Event percentage of coming to a stop (all data)

Stop Bar	50 ft before the stop bar	100 ft before the stop bar	150 ft before the stop bar
29.73 %	17.5 %	29.27 %	47.7 %

Table 6.7 – Speed reduction and duration of reduction for each travel direction of the red-light-running vehicle

		Speed reduction (mph)				Duration of speed reduction (sec)			
		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
Red-Light Runner ←	Minimum	0.85	0.43	1.40	2.12	0.48	0.97	1.32	1.63
	Maximum	36.07	30.71	36.71	34.27	12.25	14.68	16.17	9.78
	Average	16.06	15.05	21.33	22.89	2.14	2.52	2.71	2.88
	Standard Deviation	11.18	8.06	10.83	8.20	2.15	2.86	2.74	1.57
Red-Light Runner →	Minimum	1.57	0.43	1.03	0.67	0.82	0.42	0.98	1.64
	Maximum	29.36	37.19	18.48	34.10	3.97	3.08	4.25	17.82
	Average	16.43	16.18	8.24	18.73	2.17	1.79	2.38	3.78
	Standard Deviation	9.85	10.63	5.92	9.24	0.97	0.64	0.96	4.71

Table 6.8 – Percentage of coming to a stop by travel direction of the red-light-running vehicle

	Stop Bar	50 ft before stop bar	100 ft before stop bar	150 ft before stop bar
Red-Light Runner ←	30.77 %	8 %	44.44 %	48 %
Red-Light Runner →	27.27 %	33.33 %	0 %	27.27 %

6.5 Descriptive Statistics Distance-Based Analysis

The distance from the stop bar to the location of the reaction to the warning system was calculated. Figure 6.9 shows the relationship between the different activation locations of the warning system. Rather than a linear relationship, the relationship at different activation locations follows a quadratic curve.

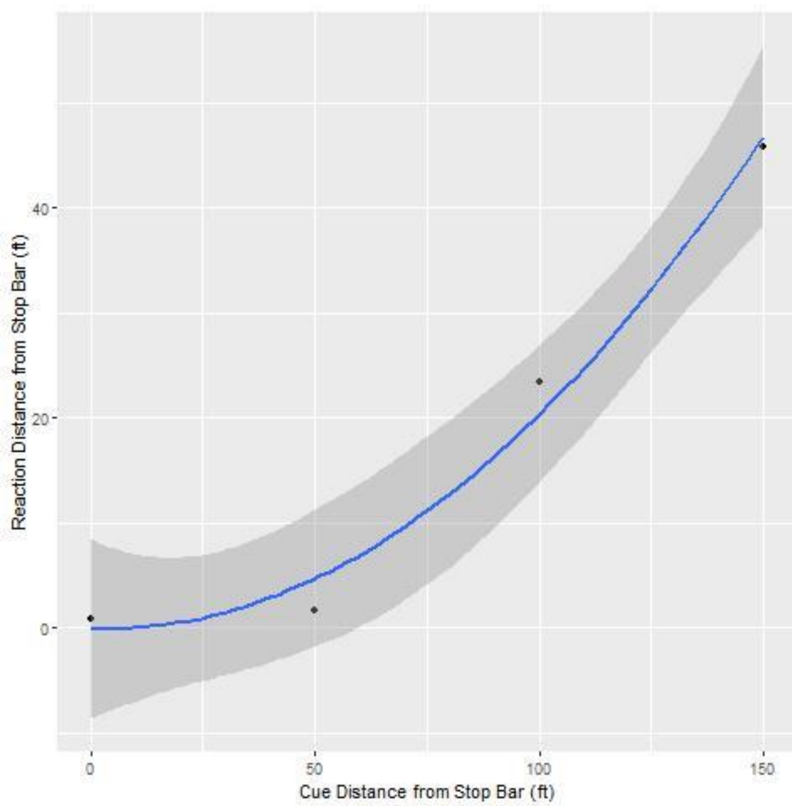

Figure 6.9 – Reaction distance from the stop bar

6.6 Results of Secondary Task

Subjects were asked to press the button on a clicker (Figure 5.3) when they spotted a pedestrian. In total, subjects were expected to spot 13 pedestrians: 7 in the first run, 2 in the second run, and 4 in the third run. Table 6.9 shows the results of detecting pedestrians while driving. For the first run, pedestrians were distributed all over the run in groups. Subjects were able to detect only 70.71% of pedestrians. This was due to the subjects concentrating on driving rather than looking around. For the second run, pedestrians were located near two intersections. Subjects paid more attention around that area, especially at a red light. Subjects were able to detect 85.29% of the pedestrians in the second run. For the third run, pedestrians were located in low-traffic areas. Subjects were able to detect 91.67% of the pedestrians because of the low workload during driving. In total, subjects were able to detect 70.38% of the pedestrians, which means that subjects focused more on driving and paid attention to pedestrians when necessary.

Table 6.9 – 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

7 Conclusions

In-vehicle technology has improved over time. These advancements have led to the inclusion of active safety systems that can help drivers avoid collisions. Until CV technology becomes ubiquitous, strategies for communicating between CVs and non-CVs as well as with connected infrastructure will be critical in improving transportation safety. Communicating information from roadway infrastructure to CVs is key, especially for scenarios in which the line of sight of in-vehicle sensors is obstructed by other vehicles, pedestrians, buildings, and other objects. This research examined an in-vehicle warning system at signalized intersections when 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 subject.

As part of the research described in this report, a driving simulator experiment was conducted to study the effectiveness of a warning system. An audiovisual warning message displayed on the windshield as a HUD was used to communicate the presence of a conflicting non-CV running a red light. Participants received a warning about the potential red-light-running vehicle at the stop bar and 50 ft, 100 ft, and 150 ft before the stop bar.

7.1 Summary of Experimental Procedures

The goal of the driving simulator experiment was to evaluate the effectiveness of a warning system that communicates the presence of a potential non-connected red-light-running vehicle to the driver. The in-vehicle warning system used to communicate the presence of a non-connected red-light-running vehicle was a combination of visual and auditory cues. The visual message was displayed as a HUD.

Subjects encountered several situations in which a non-CV ran a red light. The locations where the cues were triggered during the experiment were based on a pre-defined experimental matrix. Four different locations to trigger the warning system were investigated: at the stop bar, 50 ft before the stop bar, 100 ft before the stop bar, and 150 ft before the stop bar. Subjects' reactions to the red-light-running vehicle were recorded.

Subjects were also assigned a secondary task to keep them engaged while driving to emulate a real driving situation. A roadside visual detection task was chosen as the secondary task. Subjects were asked to press the buttons on a clicker when they spotted a pedestrian.

7.2 Summary of Results

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 for groups of events associated with different locations of activation of the warning system. Subjects saw and reacted to the red-light-running vehicle before the activation of the warning system at the stop bar. Their average reaction time for the warning system at the stop bar was 0.0515 sec. 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. Statistical tests showed a statistically significant difference in the mean of reaction time between the different groups. Similar results were observed 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. Drivers reacted differently to the warning system, and some of them came to a complete stop. Subjects 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. For the secondary task, subjects were able to detect 70.38% of the pedestrians, meaning that subjects focused more on driving and paid attention to pedestrians when necessary.

7.3 Summary of Student Involvement

Student involvement began at the planning stages of the research project and continued through the preparation of the final report. During the project, the involved student had an opportunity to learn research skills, which are key for success in an engineering career. The research project provided workforce development opportunities for the involved student to enhance their data analysis and problem-solving skills. Enhancement of data analysis skills included the use of the Python programming language to process the collected data from the experiment and the R programming language to analyze the results of the experiments. Enhancement of problem-solving skills was a part of the iterative process that characterizes the research project.

7.4 Technology Transfer

A summary of the research project has been uploaded to the SAFER-SIM website. In the future, a webinar will be hosted as part of the project completion requirements to present the research project to interested people. Data collected as part of the research project will be made available through the Harvard Dataverse website.

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