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Development of a Simulation Test Bed for Connected Vehicles using the LSU Driving Simulator

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16. Abstract

This project develops a driving simulator test bed to investigate the impact of three connected vehicle (CV) safety applications on driving behavior. The blind spot warning (BSW), forward collision warning (FCW), and do not pass warning (DNPW) applications were tested on human subjects in the LSU high-fidelity driving simulator. The BSW and DNPW applications were tested at different levels of market penetration, while the FCW application was tested for aggressive and non-aggressive categories of drivers. For the BSW, a proximity-based threshold was used to trigger a warning as a CV approached the simulator vehicle's blind spot. To test the impact of MP on the effectiveness of the BSW Application, four simulation scenarios were developed with zero, 25%, 50%, and 75% MP rates. Eighty-one participants were recruited to participate in a 15-minute experiment within the driving simulator. Drivers were instructed to perform lane change maneuvers whenever they felt comfortable. For each lane change, the simulator vehicle and blind spot vehicle's speeds and gaps were collected. Two non-parametric tests, along with a post-hoc pairwise test, were used to compare the significance each MP had on the minimum time-to-collision (TTC) and the variance of the speed of the subject vehicle and blind spot vehicle. The FCW application was designed by enabling a lead vehicle to communicate alert messages to the simulator when certain time-to-collision thresholds were reached. Thirty participants, grouped into aggressive and non-aggressive drivers, were allowed to drive the simulator twice; once with the alert messages, and another without the alert messages. Using time-to-collision as a performance measure, a t-test for dependent samples showed that for non-aggressive drivers, there were no differences in their driving behavior. However for aggressive drivers, their driving behavior showed a significant improvement in their overall safety. For the DNPW, an 8s TTC threshold was designed to warn drivers of oncoming vehicles on a two-lane two-way rural roadway. A pilot study consisting of twenty-four experiments was conducted at varying MPs. Participants performed five overtaking maneuvers within each experiment, totaling to 30 maneuvers for each MP. The safety of each maneuver was evaluated by the TTC between the simulator and oncoming vehicle at the beginning and end of the maneuver, the time spent in the opposing lane, the headway between the simulator vehicle and the vehicle in the right lane before the maneuver, and the tailway between the two vehicles following the maneuver. The results of BSW and DNPW applications indicated that a medium MP (50%) is required to achieve significant safety improvement from CV safety applications, while the results of the FCW testing indicated that only aggressive driver category can benefit from such type of alerts.

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ABSTRACT

This project develops a driving simulator test bed to investigate the impact of three connected vehicle (CV) safety applications on driving behavior. The blind spot warning (BSW), forward collision warning (FCW), and do not pass warning (DNPW) applications were tested on human subjects in the LSU high-fidelity driving simulator. The BSW and DNPW applications were tested at different levels of market penetration (MP), while the FCW application was tested for aggressive and non-aggressive categories of drivers. For the BSW, a proximity-based threshold was used to trigger a warning as a CV approached the simulator vehicle's blind spot. To test the impact of MP on the effectiveness of the BSW application, four simulation scenarios were developed with zero, 25%, 50%, and 75% MP rates.

Eighty-one participants were recruited to participate in a 15-minute experiment within the driving simulator. Drivers were instructed to perform lane change maneuvers whenever they felt comfortable. For each lane change, the simulator vehicle and blind spot vehicle's speeds and gaps were collected. Two non-parametric tests, along with a post-hoc pairwise test, were used to compare the significance each MP had on the minimum time-to-collision (TTC) and the variance of the speed of the subject vehicle and blind spot vehicle.

The FCW application was designed by enabling a lead vehicle to communicate alert messages to the simulator when certain time-to-collision thresholds were reached. Thirty participants, grouped into aggressive and non-aggressive drivers, were allowed to drive the simulator twice; once with the alert messages, and another without the alert messages. Using time-to-collision as a performance measure, a t-test for dependent samples showed that for non-aggressive drivers, there were no differences in their driving behavior. However for aggressive drivers, their driving behavior showed a significant improvement in their overall safety. For the DNPW, an 8 sec TTC threshold was designed to warn drivers of oncoming vehicles on a two-lane, two-way rural roadway. A pilot study consisting of 24 experiments was conducted at varying MPs. Participants performed five overtaking maneuvers within each experiment, totaling to 30 maneuvers for each MP. The safety of each maneuver was evaluated by the TTC between the simulator and oncoming vehicle at the beginning and end of the maneuver, the time spent in the opposing lane, the headway between the simulator vehicle and the vehicle in the right lane before the maneuver, and the tailway between the two vehicles following the maneuver.

The results of BSW and DNPW applications indicated that a medium MP (50%) is required to achieve significant safety improvement from CV safety applications, while the results of

the FCW testing indicated that only the aggressive driver category can benefit from such type of alerts.

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IMPLEMENTATION STATEMENT

Connected vehicle technology has been acknowledged to have operational benefits in terms of reducing travel times and delays for the traveling public, as well as lessening the environmental impact in terms of reducing vehicle emissions and air pollution. The deployment of such technology offers an opportunity for economic development by targeting improvements in the areas of traffic operation, safety, and environmental impacts. However, to be able to fully assess its reliability and potential benefits, it requires the development of test beds that will additionally address unforeseen and potential issues associated with the development and deployment of the technology. Simulation-based test beds, harnessing a driving simulator platform, can be utilized to achieve the benefits of a physical test bed and, if successful, will provide a cheaper alternative that can be easier controlled for desired effects. This project provided an insight on the use of driving simulators in studying the impact of connected vehicle safety applications on driving behavior. Three applications were tested including blind spot warnings (BSW), forward collision warnings (FCW), and do not pass warnings (DNPW). The BSW and DNPW applications were tested at different levels of market penetrations, while the FCW application was tested assuming 100% market penetration for different categories of drivers. Experiments results showed that both BSW and DNPW applications can be effective in improving driver safety at a minimum 50% market penetration, while FCW application can only be effective for aggressive drivers. The findings of this project prove CV safety applications effective in improving driving behavior and safety, thus supporting implementation endeavors of the technology at the state and national levels.

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INTRODUCTION

Connected Vehicle (CV) technology has many promising features and applications that can drastically improve transportation network safety and operation. Through vehicle-to-vehicle (V2V) and vehicle-to-infrastructure (V2I) communication (shown in Figure 1), CVs are able to exchange information that can influence drivers' decision-making process to improve their mobility and, more importantly, safety in the transportation network. This exchanged information includes current vehicle parameters as well as roadway conditions, which could be used to detect dangerous driving scenarios and provide warning messages to the driver. These warnings are part of CV safety applications, designed specifically for each scenario.

The effectiveness of these warning systems is highly dependent on the vehicle's ability to communicate with another vehicle within the Dedicated Short-Range Communications (DSRC) transmission. For this process to be possible, the vehicle within range must also be equipped with CV technology. Due to this limitation, the effectiveness of CV safety applications is dependent on the market penetration (MP) of CV within the network.

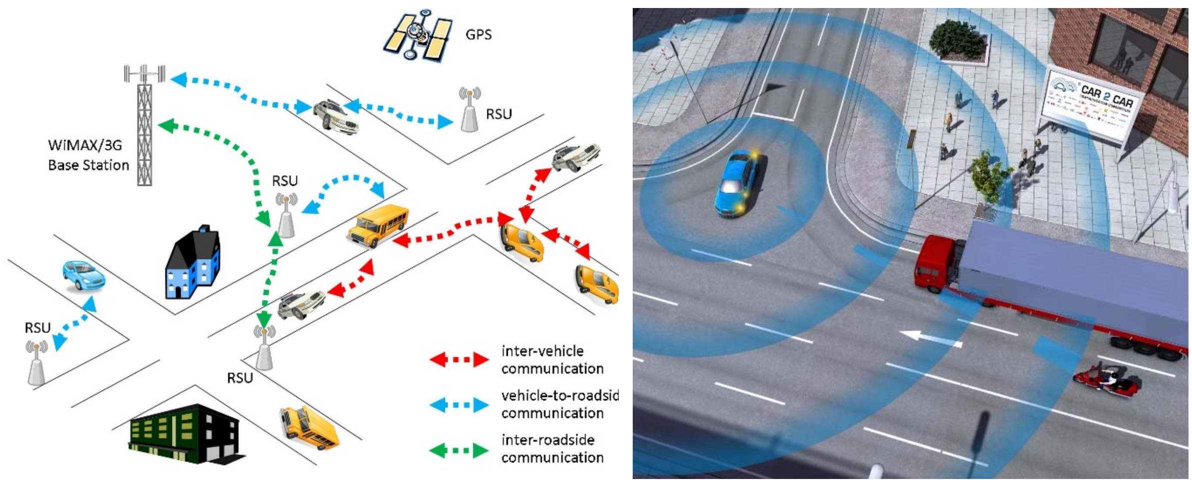


Figure 1
Connected vehicle technology

The national statistics show that annual vehicle crashes in the United States (U.S.) claim more than 32,000 lives and result in 2.3 million emergency room visits, leading to a loss of $240 billion each year. In addition, congestion on U.S. roads is responsible for the loss of $87.2 billion annually from the U.S. economy, wasting 4.2 billion hours of travel time and 2.8 billion gallons of fuel. As such, successful implementation of connected vehicle applications will have a substantial economic benefit, especially for states with high crash rates such as Louisiana.

The benefits offered by the CV technology on the U.S. economy can be explained through the tremendous amount of connected vehicle safety-related, weather-related, environment-related, emergency-related, and mobility-related applications. Connected vehicle safety-related applications, which are warning messages that aim at increasing driver safety, include crash alerts, forward collision warning (FCW) application, intersection movement assist, do not pass warning (DNPW) application, emergency electronic brake light warning, blind spot warning (BSW), and rail crossing violation warning. Weather-related applications, on the other hand, aim at either increasing drivers' safety or at improving the network operation during specific weather conditions. Examples of such applications include road-weather motorist warnings that are transmitted to traffic management centers via V2I technology. The transmission of warnings enables a dynamic traffic management system that obtains (1) real-time information that helps in making decisions on dynamic speed limits and (2) weather information that drivers receive via the in-vehicle technology that helps in making route decisions based on weather information. Environment-related applications aim at improving the overall network operation by reducing delay times, and turning the transportation system into an environment-friendly system via reducing vehicle emissions and fuel consumption. Examples of these applications include dynamic eco-lanes, eco-speed harmonization, and eco-approach and eco-departure at signalized intersections. Emergency-related applications include incident zone warning and emergency vehicle pre-emption. Finally, mobility-related applications are related to increasing network mobility and embody more interaction with pedestrian via wireless communication. Examples of mobility-related applications include dynamic transit operation, bus connection protection, dynamic ridesharing, cooperative adaptive cruise control application, queue warning, pedestrian assistance, and dynamic parking availability system.

The deployment of CV technology offers states such as Louisiana an opportunity for economic development by targeting improvements in the areas of traffic operation, safety, and environment. Nevertheless, before implementation of such technologies, researchers first need to answer several questions on how effective the applications will be and what benefits can be realized prior to implementation, what infrastructure is needed, what minimum market penetration is required, and what technological specifications should be adopted, among others.

Problem Statement

CV research relies on the use of test beds to address the potential problems associated with the development and deployment of V2V and V2I technologies. Test beds for connected vehicle research can also be used for testing real time data capture and management systems, as well as testing the integration and interoperability of connected vehicles, mobile devices, and highway infrastructure. Along with the physical platforms for test beds, simulation-based test beds can also be harnessed to achieve similar goals. More specifically, driving simulators are high fidelity human-in-the-loop simulation platforms that have a great potential to serve as a connected vehicles test beds. With the availability of the LSU driving simulator, the development of a simulation test bed for connected vehicles is possible. Once developed, this test bed will provide the research team with an excellent opportunity to pursue federal funding from NSF and NCHRP for cutting edge research in the area of connected vehicles to benefit Louisiana citizens. An example of the available federal funding that can be targeted is the NCHRP 20-24(98) connected/automated vehicle research roadmap for AASHTO that aims at answering the related connected/automated vehicle open questions and issues. In essence, the primary goal of this study was to develop a driving simulator-based test bed for connected vehicle research with emphasis on operation and safety. This test bed can then be used to test the impacts and benefits of various connected vehicle technology applications on driver behavior as well as the overall transportation network performance.

The Department of Transportation (DOT) has identified dangerous scenarios that can be avoided through V2V based warning systems *[1]*. This study investigates the effectiveness of three warning applications including BSW, DNPW, and FCW. The BSW application could alert drivers of vehicles located within the driver's blind spot during lane change maneuvers. The crash statistics in 2012 show that merging and lane-change collisions caused 592 fatal accidents, 61,000 injuries, and 286,000 incidents involving property damage, which accounts for approximately 4% of all collisions *[2]*. Therefore, BSW could be a valuable solution to reduce crashes during lane change maneuvers. The DNPW, on the other hand, could alert drivers of oncoming vehicles on two-lane, two-way rural highways. The DNPW will assist drivers in performing overtaking maneuvers, which has been reported to account for 672 fatal incidents, 19,000 injuries, and 72,000 incidents involving property damage *[2]*. Although these incidents are less frequent compared to lane changes, they create a high risk of head-to-head collisions, which can be fatal. Finally, FCW alerts drivers of slowing vehicles ahead to avoid bumper-to-bumper crashes.

From this perspective, a preliminary driving simulator test bed was developed in the driving simulator laboratory at Louisiana State University (LSU) to allow vehicles to communicate and transmit warning messages within the virtual environment. The three applications were then designed and tested on human subjects at different market penetrations. It is worth pointing out that the FCW, was only tested at 100% market penetration while considering driver aggressiveness as an important factor in determining driving behavior.

Literature Review

In this section, a thorough literature review is provided about CV safety applications and, specifically, the three applications of interest in this study.

Connected Vehicle Safety Applications

In view of the fact that Connected Vehicle (CV) technology is not yet deployed, except minimally for testing purposes, CV's safety applications can only be applied in controlled environments such as driving simulators and test tracks. Particularly, high-fidelity driving simulators are considered prime test beds to perform experimental research on the safety benefits of CV technology. There are several studies to assess the safety impact of CV applications using a driving simulator *[3-7]*. Creaser et al. and Yan et al. performed separate studies using driving simulator based test beds as a means to test the safety impact of CV warning systems *[4, 5, 7]*. Creaser et al. concentrated on alerting drivers in advance of potential risks caused by changes in roadway conditions *[7]*. Examples of these changes include speed limit adjustments due to school and construction zones as well as oncoming changes in roadway geometry. By analyzing eye tracking measures and response times, it was clear that the benefit of advanced notifications outweighed the safety risk of driver distraction caused by the warning system. Yan's initial study examined the effectiveness of an auditory red-light-running vehicle warning system, which utilized a time-to-collision (TTC) sensor to notify the driver of potential collisions *[4]*. The results showed that the warnings led to reduced reaction times, larger maximum decelerations, and less lane deviation, indicating a decrease in crash risk for the driver. In a follow up study, Yan et al. also determined that warning messages should be provided 4.0 sec to 4.5 sec before collision *[4]*.

Dangerous Lane Change Maneuvers

One CV application that is expected to improve roadway safety is the BSW application, which provides lane change assistance by alerting drivers of adjacent vehicles not visible within the side or rear view mirrors. The presence of a vehicle within a driver's blind spot can lead to imminent danger and greatly decrease safety on the roadway. Although blind spot collisions can be avoided by taking extra precautions, such as signaling and looking over one's shoulder prior to performing a lane change maneuver, several drivers do not perform these safety measures. This lack of caution prescribes a need for additional information on the vehicle's surroundings to be provided before conducting a lane change maneuver. Although there are existing radar-based BSW systems on the market, CV technologies provide an alternate and potentially more efficient solution to reducing blind-spot related risk. By using CV technology in lieu of radar-based methods, data is available for a wider range of vehicle parameters, which presents the opportunity to overcome the limitations of the radar-based detectors. Most of the developed radar-based systems face many challenges in coping with the diversified lane and road appearances. These challenges arise from poor visibility conditions, snowy roads, shadows, nighttime light reflection especially with a wet road surface, etc. Wireless communication, which is the main technology used in CVs, is considered one way to minimize the effect of, or totally overcome, these challenges.

To investigate the impact of a CV blind spot application on drivers' safety, it is essential to understand drivers' behavior and vehicle performance measures during normal lane change maneuvers. Studies performed by Lee et al. and Chen et al. used naturalistic data to analyze driving behavior during lane change maneuvers *[8, 9]*. Lee and Chen both used time-to-collision to measure the safety of lane change maneuvers, as it indicated the crash risk between the vehicle performing a lane change and the impacted vehicles by that lane change maneuver. Lee found that the fifth percentile TTC value for vehicles was 6.08s for rearward vehicles. Chen focused on the drivers' minimum TTC and found that there was a large variability in minimum TTC, showing a need for different warning thresholds for different driving styles. Rather than analyzing naturalistic data, another test performed by Salvucci et al. analyzed lane change behavior within a simulator by depicting the lane position, throttle, and steering for each participant over the course of the 15-minute simulation *[10]*. The results showed that drivers decelerated slightly before a pass lane change, accelerated soon after the lane change, and maintained the higher speed following the lane change maneuver.

In testing the safety benefits of BSW application, an example study was performed by the National Highway Traffic Safety Administration (NHTSA) *[11]*. In this study, CV technology was utilized to design and study a BSW system. The purpose of the study was to evaluate drivers' responses to warning messages after being instructed to change lanes with a vehicle present in their blind spot on the Virginia Tech Transportation Institute's 3.54 km. test track. After analyzing the data, the researchers concluded that the use of two variants of warnings, one for non-urgent messages and one for urgent messages, was a more effective way of alerting drivers than a single variant warning system. The main shortcoming of this study and the other reviewed studies that evaluated the performance of CV safety applications was the assumption that 100% of the vehicles were equipped with CV technology, which may not be considered realistic considering the lengthy time required to achieve this penetration rate. Thus, it is important to examine the performance of CV applications at low and medium market penetration (MP)s (≤50%) which are likely to exist during the early stages of CV deployment *[12]*.

Vehicle Overtaking on a Two-Lane Two-Way Rural Highway

Another CV application where the effect of MP is unknown is the DNPW system, which alerts drivers of oncoming traffic on a two-lane roadway to prevent drivers from performing an overtaking maneuver. Overtaking maneuvers involve a scenario in which the driver must pass a slower-moving vehicle by entering the lane with opposing traffic. These maneuvers are particularly dangerous due to the high speeds of rural highways and the potential of head-to-head collisions. Traditionally, measures are taken during the roadway design period to improve safety during passing maneuvers, in accordance with the American Association of State Highway and Transportation Officials (AASHTO) and the Manual on Uniform Traffic Control Devices (MUTCD). These manuals have defined the safe passing sight distances for two-lane rural roads. AASHTO defines the minimum passing sight distance for a 50 mph rural road as 1835 feet, whereas MUTCD has set the minimum passing sight distance for marking no-passing zones at 50 mph as 800 ft. *[13, 14]*. While these regulations do prevent dangerous maneuvers, Richter et al. found that most accidents still occur where overtaking is permitted *[15]*. An alternate solution to improving safety during these maneuvers involves the development of overtaking lanes, which introduces a third traffic lane temporarily to allow for overtaking maneuvers without the danger of oncoming vehicles. Although, to the researcher's knowledge overtaking lanes have not been implemented in the United States, they have been successfully implemented in Australia. Charlton et al. found that the design utilized in Australia operated efficiently in the diverge area, but not in the merge area *[13]*. This is a promising method to improve safety, but the cost is high and the land is often not available to develop additional lanes.

While efficient roadway design and markings can assist drivers in overtaking maneuvers, they do not provide enough information to aid in the decision-making process of whether to initiate an overtaking maneuver. CV technology provides an innovative opportunity to provide drivers with additional information on the speed and proximity of oncoming vehicles, which can assist drivers in the decision making process. To design a DNPW, it is important to understand which vehicle parameters are appropriate indicators of a dangerous overtaking maneuver. TTC is considered an effective parameter to measure the safety of an overtaking maneuver. Mahmud et al. has determined from existing studies and AASHTO regulations that the desirable minimum TTC is 3 sec *[14, 16, 17]*. This 3-second TTC can be used to evaluate the safety at the end of a maneuver. To avoid TTC less than this threshold, Hegeman et al. has determined that overtaking assistance warnings should be provided when the TTC between the driver's vehicle and the oncoming vehicle is less than 8 sec *[16]*. This same threshold is used in the design of the DNPW system in this study.

Another parameter commonly used as a safety indicator is the headway between the driver's vehicle and another vehicle moving in the same direction *[17]*. The findings of Taieb-Maimon and Shinar determined that the desirable headway is greater than 0.7 sec, while Ohita found the desirable headway to be greater than 0.6 sec *[18, 19]*. It is important to note that these findings differ from the generally recommended 2 sec safe headway. Headways during overtaking maneuvers are expected to be even smaller, since perception reaction time during overtake maneuvers are generally shorter, which allows the driver to maintain a shorter headway *[20]*.

For this study, TTC is used to design the DNPW, while TTC and headway both are used to evaluate the safety benefits of the warning system. A similar study performed by Hegeman et al. evaluated the effectiveness of an overtaking assistance warning system within a simulator, but this study did not consider the limitations of CV technology *[16]*. The efficiency of using a warning system based on TTC is limited because the oncoming CV must also be located within the 1000 ft. (300 m) DSRC range, which is not always the case at a TTC of 8 sec. In addition, human behavior and compliance must be tested at varying levels of MP to determine if the warning system could improve safety early in deployment.

Connected Vehicle Forward Collision

With the rapid advances in the transportation system, such as the Advanced Traveler Information Systems (ATIS) and the in-vehicle information systems (IVIS), drivers are prone to have divided attention between the driving and the information processing tasks. In that context, Yang and Fricker conducted an experiment to determine the amount of information that is considered to be too much for a driver to process, and to determine which way of conveyance is most effective *[21]*. They used a driving simulator to simulate familiar and unfamiliar areas to the subjects. The responses when given twelve different information combinations for both familiar and unfamiliar areas were evaluated. Their findings showed that when a driver is in a familiar area, the need for a visual display (e.g. a map) is not necessary because a driver relies on their prior knowledge of the area. The opposite is observed when the driver is in an unfamiliar area. They also found that a visual display was more effective when accompanied with an auditory message that alerted drivers.

Lloyd et al. studied the most effective means to convey potential collision information at intersections *[22]*. They began by analyzing the occurrence of collisions at intersections using the National Automotive Sampling System (NASS) crash data, and found that together, driver inattention 28.7%, faulty perception 33.9%, and vision impaired/obstructed 11.1%, accounted for nearly 75% of intersection crashes. This showed that a majority of crashes are caused by a lapse in judgment in some manner. In their study, the authors analyzed different means for conveying the potential collision information and found two types of warning systems that could benefit a large group of people in the most effective manner: heads-up-display (HUD) and haptic cueing. The main finding of this study was that using a combination of these technologies can be the most effective way because drivers could be stimulated with a haptic cue, and then alerted to the situation approaching so that a proper reaction could be performed. However, the warnings have to be simple and short as lengthy and complex messages could rather prove distracting and reduce safety.

In another study, Lloyd et al. explored when and how to present warning messages of a stop when approaching signalized intersections in order for drivers to optimally perform safe reactions *[23]*. The authors analyzed drivers' behavior data and focused on four main parameters: throttle lift-off, brake application, steering, and turn signal activation. In their analysis, the authors found that the optimal time to alert drivers when to stop was 15 sec before reaching the intersection. They also suggested that alerts should be such that they should benefit all drivers, not require specific directional orientation, be compatible with drivers' response, and have a viable integration with other Collision Avoidance Systems (CAS) and Driver Assistance Systems (DAS). Based on these characteristics, the authors analyzed the effectiveness of both visual and auditory messages. For the auditory messages, the results showed that a tone alert would not benefit all drivers especially drivers with a hearing disability; whereas, a voice command was found to potentially cause a driver to experience attention overload. For the visual messages, HUD was found to be effective but could potentially lead to distraction and compromise safety if not located in a forward view position.

Fitch et al. tested the Connected-Vehicle Collision Avoidance System (CAS) applications using a Wizard-of-Oz technique *[24]*. The main objective of the study was to test whether to present multiple crash alerts in multiple conflict scenario, or present only one alert to the first conflict and suppress the subsequent alerts. The results of study suggest that presenting multiple unique auditory alerts in a multiple conflict scenario was appropriate to most of the drivers provided. This supports the first part of earlier studies that state that multiple alerts in multiple conflicts can provide drivers with the appropriate guidance to conduct the appropriate avoidance maneuvers *[25, 26]*. However, the results conflicted with the second part of the studies which states that any alerts presented after the first alert could confuse and distract the drivers. Therefore, Fitch et al. concluded that their results need to be investigated further.

Jeong et al. conducted a simulation study to evaluate the proposed Inter-vehicle Safety Warning Information System (ISWS) aimed at improving drivers' attentiveness through providing warning alerts about potential hazards in a connected vehicle environment *[27]*. They used a crash prone location in the Korean freeway system to collect data about drivers' behavior in different situations and then transformed into a VISSIM simulation model. The results showed that with a 100% market penetration, the number of rear-end conflicts was reduced by around 84% under level of service D. However, for free flowing conditions, the ISWS did not show any significant impact on drivers' safety as the conditions are already stable.

Connected Vehicle Market Penetration

Most of the past research investigating the impact of MP focused on the technology performance or the transportation network operation, rather than the effectiveness of safety applications *[28-31]*. For instance, Goel's study on the viability of Wi-Fi based V2V networks evaluated the impact of MP, Wi-Fi range, and density of vehicles in the region on the information propagation rate and the final diameter of communication *[28]*. The study found that an increase in MP led to a higher information propagation rate. Similarly, the study conducted by Osman and Ishak on a network level connectivity robustness measure for CV environments also showed that the network benefits are proportional to MP *[29]*. The study found that the overall robustness increased as the MP increased, given the same transmission range and relative traffic density. These studies provide insight on the effect of MP on the efficiency of the technology. However, more research is required to assess the impact of MP on the effectiveness of CV safety applications.

OBJECTIVES

The use of a driving simulator provides several advantages for testing driving behavior that is difficult to capture on a test track or by collecting naturalistic driving data. By placing participants in a simulated environment, the safety risk associated with driving is eliminated. Essentially, drivers are given the same opportunities to perform dangerous maneuvers as they would in reality, while the experimenter is able to have more control over the conditions within the simulator. These advantages led to the development of the CV test bed in this study. By performing experiments within this test bed, this study attempts to evaluate the effectiveness of BSW, DNPW, and FCW applications to improve driving safety in the CV environment. More specifically, the main focus of this study was to develop a driving simulator-based test bed for connected vehicles research in the areas of operation and safety. The specific objectives were to:

1. Develop a connected vehicle simulation test bed using a driving simulator;
2. Create some of the connected vehicle safety related applications in the driving simulator environment such as intersection movement assist, DNPW, and BSW applications;
3. Create some of the emergency-related applications in the simulator environment such as eco-approach and eco-departure at signalized intersections; and
4. Test the impacts and benefits of each specific application on drivers' behavior.

SCOPE

This study focused on exploring the effectiveness of CV safety applications on driving behavior and traffic safety at different market penetration rates. The study was conducted using a test bed designed in the LSU driving simulator for CV Blind Spot Warning, Do Not Pass Warning, and Forward Collision Warning applications

METHODOLOGY

This chapter provides information regarding the development of the CV network, within a driving simulator test bed. It also provides the design and experimentation process of the BSW, DNPW, and FCW systems.

Driving Simulator Test Bed Design

The driving simulator at Louisiana State University has been used for research studies in the field of transportation engineering *[32, 33]*. Recently, an emphasis has been made to develop studies that incorporate CV applications into the simulator environment. A CV test bed would have the ability to collect information through V2V communication and relay messages, warning the simulator participant of various driving hazards.

As shown in Figure 2(a), the simulator consisted of a Ford Focus automobile with front and rear-view-projection screens, along with side mirror projections for portraying a virtual environment. To simulate a realistic driving experience, the simulator produced forward and backward motion when the driver applied the brakes or throttle. The driving simulator utilized automated sensing devices to gather data including engine revolutions per minute (RPM), heading error, vehicle speed, acceleration, trajectory offset, braking, and vehicle position. Four cameras were built into the vehicle to capture footage of the driver, which could be used to analyze participant's behavior and reactions. The virtual environment was created using SimVista software and the vehicle simulation was run using the SimCreator software. Simulation sound was also produced to simulate engine sound, tire sound, and noise from the vehicle.

(a)

(b)

Figure 2
Louisiana State University driving simulator,
(a) the simulator car, (b) the computers control

Creation of Connected Vehicles within the Simulator Environment

The previously developed test bed in LSU was adjusted to simulate a more realistic CV network *[32]*. The improved test bed consists of the LSU driving simulator vehicle, along with 52 simulated vehicles in the ambient traffic that were generated randomly within an urban environment. The vehicles were generated with a randomly assigned unique ID, which classified their type as either a connected or a non-connected vehicle. To simulate the various levels of MP, a pre-established connectivity ratio was set and assigned to the random vehicle generator. After the vehicles were assigned an ID and labeled as connected or non-connected vehicles, their current lane was identified.

Based on the location, lane and connectivity of the ambient vehicles, the communication process could begin. The simulator vehicle then started to collect information about the ambient traffic that replicates what would be available in probe data messages. Such information was transmitted by neighboring CVs simultaneously within the DSRC transmission range of 300 meter. These CVs were able to transmit these messages to other neighboring CVs, until there was no longer a new CV in range, as seen in Figure 3.

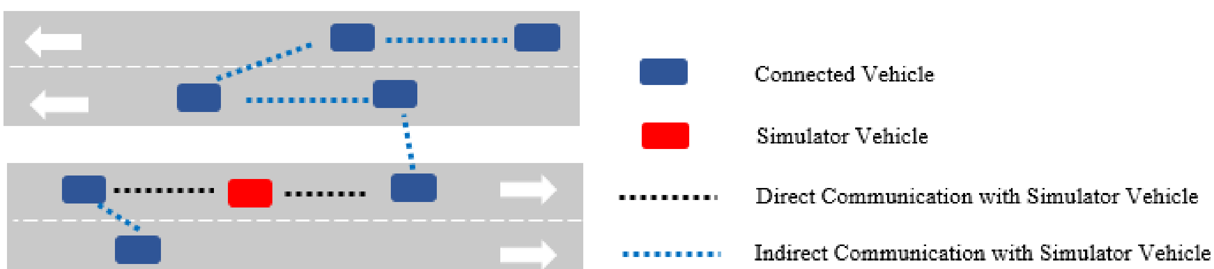


Figure 3
Simulated connected vehicle communication network

By establishing the network of CVs, it was possible to create specific functions that incorporate safety applications into the simulator. These applications use information from the probe data messages and used this data to determine if the requirements are met to display warning messages to the driver of the simulator vehicle.

Location of Visual Displays

To determine the ideal location in the simulator to display the alert messages to the drivers, a survey was created with the view of identifying the preferred location empirically. A simple questionnaire based on Figure 4 was designed on the “Survey Monkey” website and the LSU

Civil Engineering pool of graduate and undergraduate students were asked to choose their preferred location.

Figure 4
Location of alert messages display

Out of the received 79 responses, 42% chose Location 1 as ideal for the visual display, 34% chose Location 2, and the remaining 24% chose Location 3. Displaying the visual information at Location 1 conformed to previous studies that suggested that most drivers comply with messages displayed at that location *[34]*. The study also identified that location to be the safest for drivers to mount off-the-shelve GPS devices as that location was associated with the least amount of distraction.

Design of CV Safety Applications

Development of the Blind Spot Warning Application (BSW)

The first tested safety application was a warning system designed to alert drivers when CVs were present in the simulator vehicle's blind spot. The simulator environment was coded so that the test bed locates CVs within the simulator vehicle's blind spot and provides drivers with visual and auditory warnings as they intended to perform a lane change maneuver. Although the information from vehicles traveling in the opposite direction were not necessary for locating CVs within the simulator vehicle's blind spot, this data was still transmitted throughout the communication process and filtered out during the visual warning calling procedure to simulate a realistic CV network. Figure 5 illustrates this process of gathering information and providing BSWs.

To obtain the necessary information for the visual warnings, the CVs in the neighboring lane to the simulator vehicle were located and determined to be either to the left or to the right side of the simulator vehicle's current position. Once the neighboring CV was located, a series of requirements had to be met to trigger a visual response warning. First, it was determined whether the nearby vehicle was located behind the simulator vehicle, within the bearings of 91-179 degrees (right) or 181-269 degrees (left). These bearing values were determined based on data collected from the test bed to determine where vehicles behind the simulator vehicle could be located. If the vehicle was approaching, the simulator vehicle's blind spot (within 98 ft. in the adjacent lane) and driving in the same direction as the simulator vehicle, an orange visual warning was displayed on the bottom center of the front windshield. The distance of 98 ft. was determined such that a warning was established within a safety threshold before the approaching vehicles fell within the simulator vehicle's blind spot. This warning was established whether the simulator vehicle's driver intends to change lanes or not and remains on display until the visual BSW requirements were no longer met. The warning stated "Vehicle passing on the right" if the vehicle was to the right, and "Vehicle passing on the left" if the vehicle was to the left as seen in Figure 6.

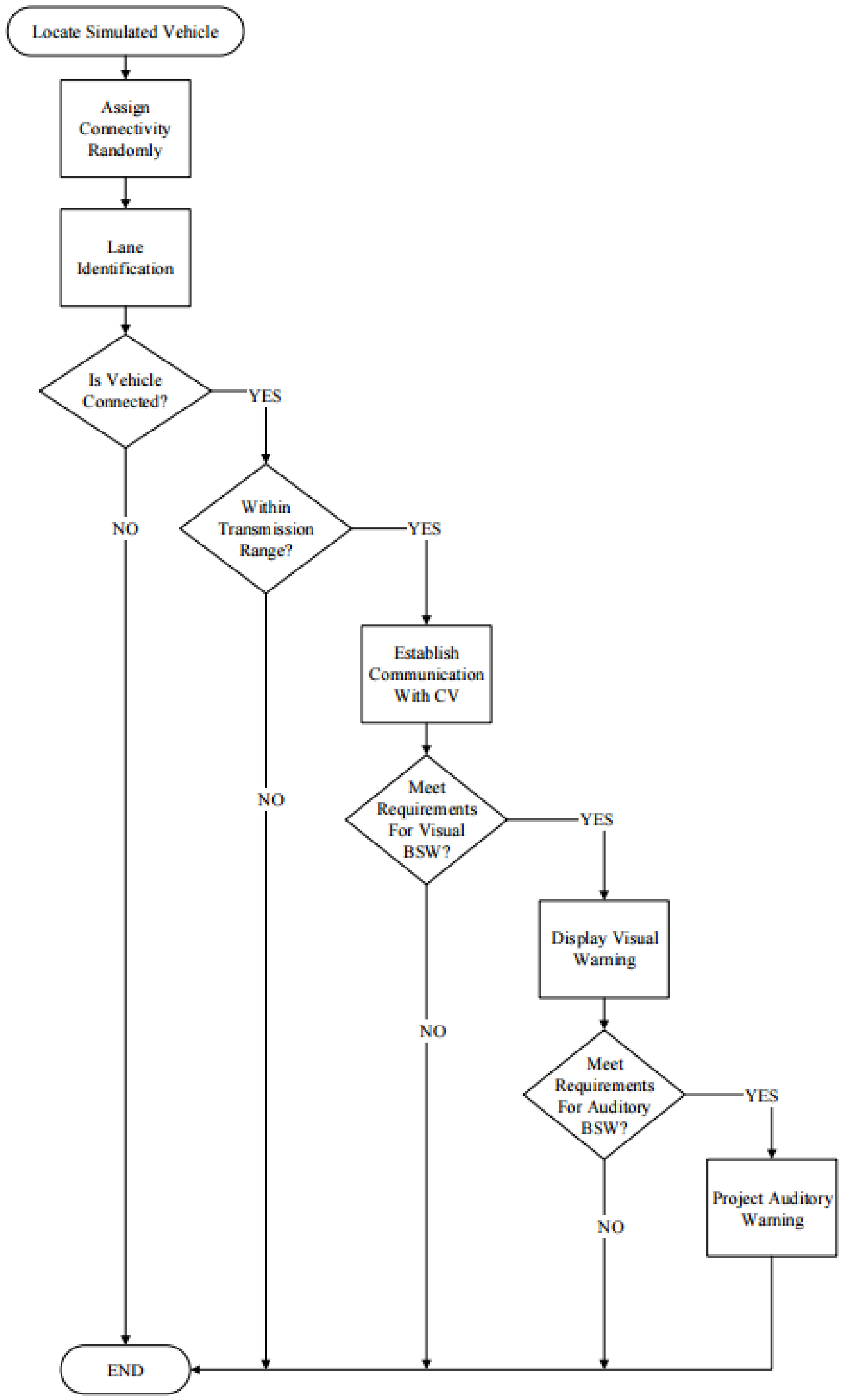


Figure 5
BSW calling process

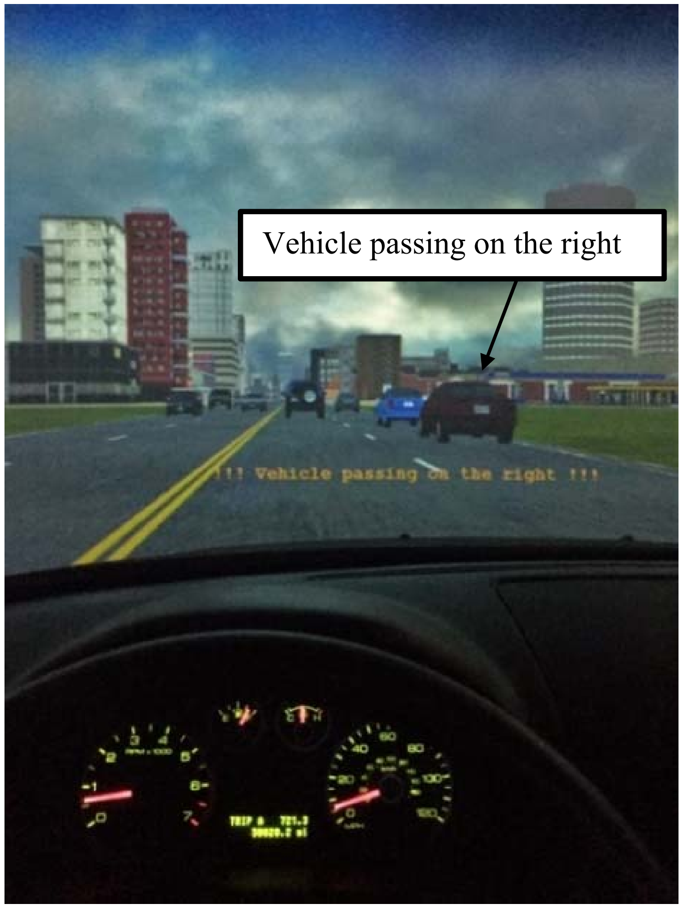


Figure 6
Visual BSW in the simulator

In addition to the visual warning, an auditory warning was provided if the driver attempted a lane change maneuver while a CV occupied the simulator vehicle's blind spot. The distance set to trigger the auditory warning was reduced to 49 ft. behind the simulator vehicle. This distance was determined based on several pilot tests performed to design a blind spot within the simulator environment. Since the driving simulator lacked 360 degrees of vision, a blind spot was simulated by establishing a location in which the approaching vehicle was not visible within the side mirrors of the simulator vehicle. The distance also accounted for a safety cushion to ensure the driver had enough time to cancel their lane change maneuver as a vehicle was entering the driver's blind spot.

Since not all drivers use turn signals, vehicle kinematics were used to identify attempted lane change maneuvers rather than the activation of a turn signal. The used vehicle dynamics included throttle, speed, lane offset, and steering. The driver had to steer greater than 15 degrees in the direction of the passing vehicle and the simulator vehicle had to be located on the half-of-the-lane closest to the passing vehicle in order to activate the auditory warning. In addition to these conditions, the simulator vehicle had to be either moving at a speed greater than 10mph (4.47m/s) or have a throttle position greater than 0.1 to prevent false readings while the vehicle was not in motion. These values were determined based on several drives in the simulator to identify the thresholds for lane change initiation. If all of the previous conditions were met as well as the requirements for the visual warning, a loud alarm did sound off on the simulator vehicle's speaker to alert the driver of a vehicle in the blind spot. Figure 7 displays the positional requirements to trigger the auditory and visual BSWs.

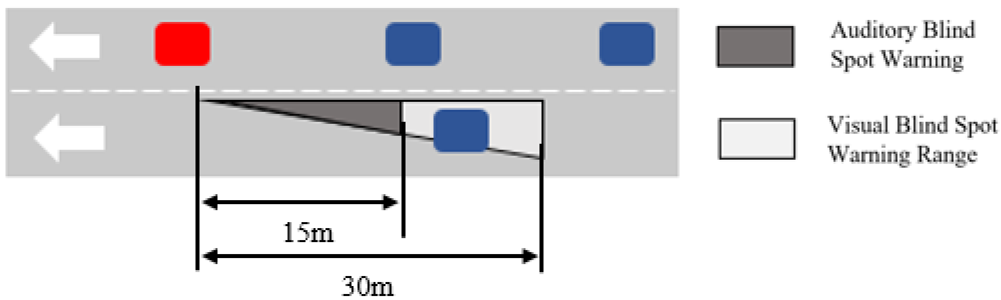


Figure 7
BSW scenario

Development of the Forward Collision Warning Application (FCW)

The visual display of the FCW is as shown in Figure 8. The alerts were designed as visual text messages that warn drivers of imminent crash with the lead vehicle. Based on Yang and Fliker's study, it was decided to omit auditory warnings because drivers were allowed to become familiar with the scenario surroundings before the actual test *[21]*. Figure 8 shows the procedure to relay two FCW messages to drivers. The first visual warning message was projected onto the driver's screen in a yellow font as "SLOW DOWN" when the driver's minimum time-to-collision (TTC) was down to 3 sec. This is shown in Figure 9 (a).

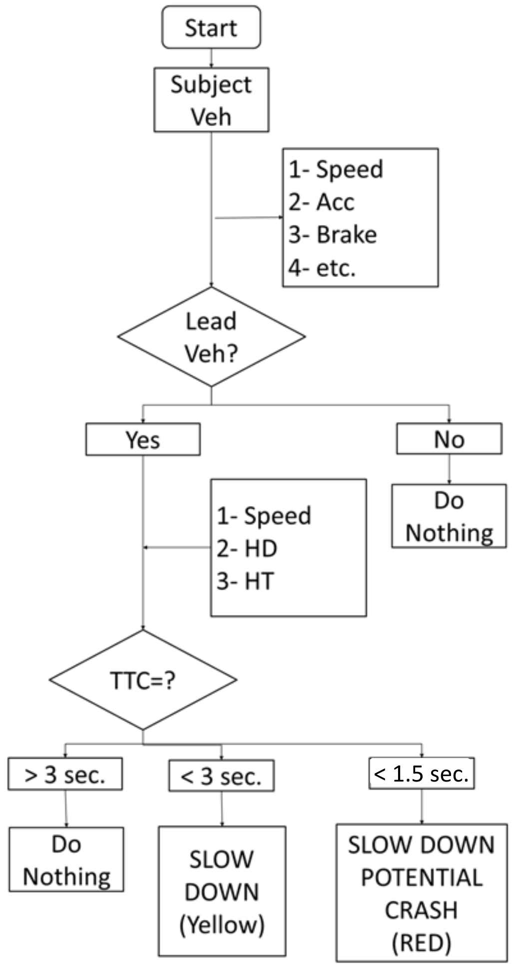
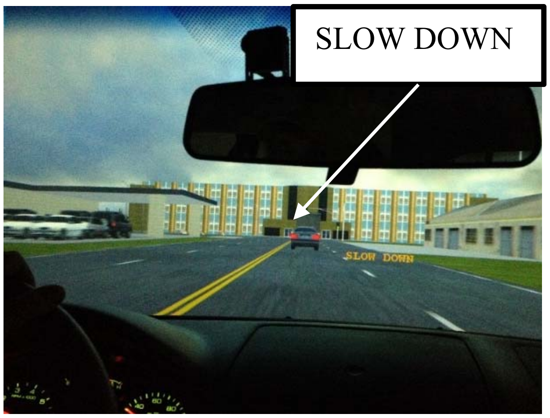
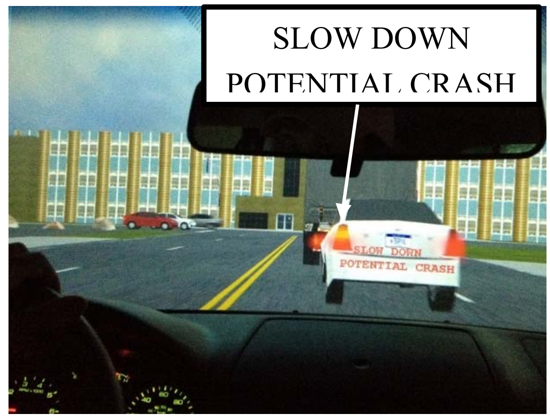


Figure 8
Location of alert messages display

The second visual warning message, displayed in red font, read "SLOW DOWN-POTENTIAL CRASH" when the TTC further dropped to 1.5 sec, the minimum TTC required for drivers to safely react *[35]*. This is shown in Figure 9 (b). The generation of these alert messages were programmed using the JavaScript files associated with the driving scenario. For the message size to be readable, a 7-in. frame that mirrors an HUD was projected onto the middle of the windshield. Three participants were asked to assess the readability of the projected message inside the frame and the text size was edited until the three drivers agreed that it was clear and readable within the 7-in. frame. This made the test-bed very close to simulate a CV HUD.



(a) At 3 sec threshold



(b) At 1.5 sec threshold

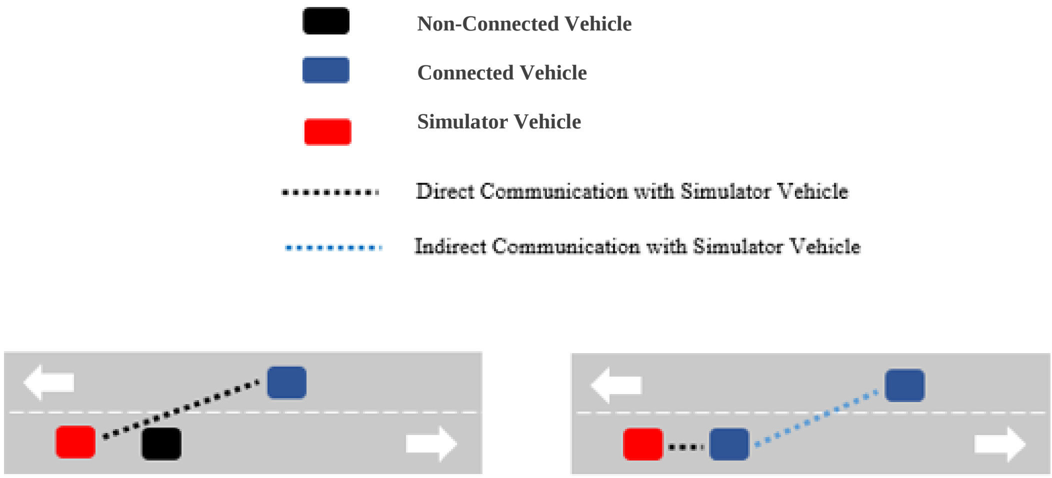
Figure 9
Location of alert messages display

Development of the Do Not Pass Warning Application (DNPW)

The DNPW application alerted drivers of oncoming traffic on a two-way, two-lane rural road. The CV test bed was adapted to warn drivers of oncoming traffic prior to an overtaking maneuver. Similar to the BSW, the application was designed to collect information from nearby CVs within the DSRC transmission range through probe data messages as seen in Figure 10. By filtering through these probe data messages, the application was able to gather the speed and location of oncoming vehicles via V2V communication if they were also equipped with CV technology. This communication could occur directly between the oncoming CV and the simulator vehicle as seen in Figure 10(a), but sometimes indirect communication shown in Figure 10(b) could be more efficient. By sending information indirectly from the oncoming CV to the CV ahead of the simulator, the range of the communication network could be extended further than 1000 ft. This allows for warning messages to be displayed to the driver even when the oncoming CV was located further than 1000 ft. from the simulator vehicle. By comparing the speed and location of the oncoming CV to that of the simulator vehicle, the TTC between the two vehicles could be calculated using equation (1).

$$TTC = (x_s - x_o)/(v_s - v_o) \quad (1)$$

where, $(x_s - x_o)$ was the distance between the simulator vehicle and the oncoming vehicle, and $(v_s - v_o)$ was the difference of the two vehicles' velocities, or in this case the sum of the two vehicles' speeds.



(a) (b)

Figure 10
CV communication network (a) using direct and (b) indirect communication.

If the TTC value was less than the minimum safe threshold of 8s, a visual warning was displayed on the dashboard of the simulator vehicle stating "DO NOT PASS," as seen in Figure 11. It is important to note that this warning system was limited by the abilities of the CV technology. Since the communication range was only 1000 ft., the maximum TTC value required to display a warning to the driver was dependent on the speed of both the simulator and simulated vehicles. Since the speed limit on the roadway for this study was 50 mph (22.4m/s), equation (1) determined that the warning would only appear when the TTC was less than 6.7 sec if both the simulator vehicle and simulated vehicle were traveling the speed limit. This threshold varied as the simulator vehicle and oncoming vehicle adjust their speeds. Figure 12 shows the scenario in which a visual DNPW will be displayed.

Figure 11
Visual DNPW screenshot

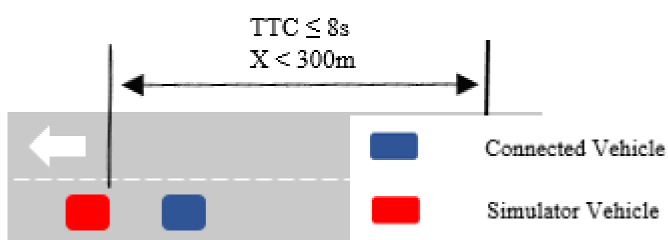


Figure 12
Implemented DNPW scenario in the simulator

In addition to the visual warnings, auditory warnings have also been developed to indicate immediate danger to the driver. If the requirements for the visual warning have been met, and the driver attempts an overtaking maneuver, a loud prompt will be initiated to alert the driver of the oncoming vehicle. The steering, lane offset, speed, and throttle requirements for an attempted lane change, designed within the BSW study, were applied to this application as well to detect an attempted overtake maneuver. Figure 13 displays the DNPW calling process.

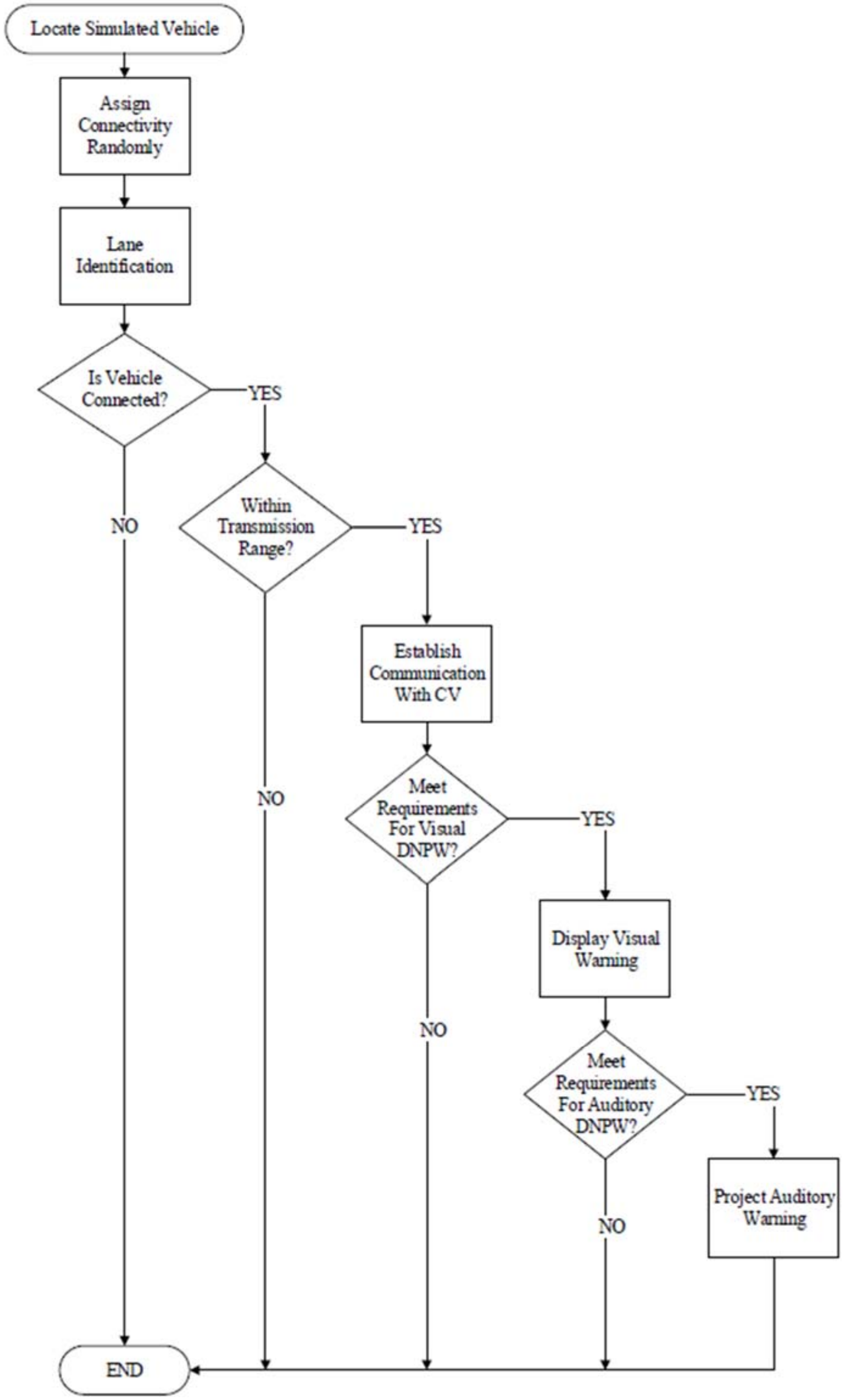


Figure 13
DNPW calling process

Experimental Design and Procedure

Experiment Design and Procedure for BSW

The BSW system was tested at varying CV MPs, including no CV communication, low MP (25%), medium MP (50%), and high MP (75%). Previous studies and forecasted MPs were analyzed to select these threshold values for the experiment *[12, 28, 29, 31]*. The driving behavior was compared under each level of MP to determine if a minimum market share was required to realize the safety benefits of CV BSW applications.

A sample of 90 participants, ranging in age from 19 to 53, including 58 males and 32 females, were recruited. The large sample size was required to assess the four different levels of MP. Since nine participants suffered from motion sickness and were unable to complete the test, the actual sample size was reduced to 81 subjects. The subjects' driving behavior was observed during lane change maneuvers, with and without the assistance of CV BSWs. These visual and auditory BSWs were provided using V2V communication at varying levels of MP for CVs.

To begin each experiment, the participants were randomly assigned one of the four market penetrations. Twenty participants were assigned to scenarios with zero, low, and high MP levels and 21 participants to one scenario with a medium level of MP. The participants were not informed of which MP they were allocated. However, they were told that not every vehicle within the simulation would provide a safety warning, and thereby they were required to account for the notion that non-equipped vehicles could be located in their blind spot when the warnings were not present. This notice was important, as it prevented the participants from becoming overly dependent on the warnings. Next, the participant filled out a consent form and responded to a brief survey. The consent form provided the participant with information on the experiment, including the risk of motion sickness associated with the simulator vehicle. The brief survey collected information on the participant's age, gender, number of years with a driving license, history of motion sickness, and experience of driving a vehicle with BSWs.

Next, the participants were briefed on the experiment and given instructions on how to operate the driving simulator vehicle. They were shown an example of the BSWs within the simulated environment. Once they were introduced to the environment and warnings, they were instructed to obey all traffic laws and informed that the speed limit was 35 mph (15.6m/s). The drivers were then instructed to make lane change maneuvers as often as possible whenever they felt it was natural for them to do so. To avoid reckless and unrealistic driving, they were told not to swerve back and forth between the two lanes. They were also informed that the research instructor would provide auditory routing commands throughout the experiment from a control station outside the simulator vehicle. In the case of an emergency, they were instructed to press the emergency button in the simulator car to abort the simulation at any time.

Following the instructions, the participants underwent a practice driving session to familiarize themselves with the simulator vehicle controls. The practice drive allowed the driver to perform repeated lane changes throughout a set course consisting of extended straight roadways, three intersections, a right curve, a left curve, and a right turn. Following the practice drive, the participants were given an opportunity to stretch before starting a 15-minute experiment within the driving simulator. For the experiment, the subjects drove throughout a four-lane arterial highway within an urban environment. The fixed driving scenario consisted of several intersections, traffic signals, stop signs, curves, turns, and extended straight roadways to increase the likelihood of lane change maneuvers. In addition to the infrastructure, the scenario included a relatively high ambient traffic density surrounding the simulator vehicle. The ambient vehicles were designed to abide by the same traffic regulations as the participant. Throughout the test, the simulator instructor provided the drivers with directions on which routes to take within the simulation environment. To limit distraction to the driver during lane change maneuvers, the driver was informed of oncoming turns well in advance. Since the fixed route included several turns, drivers were forced to initiate several lane change maneuvers within the heavy traffic conditions. Such traffic conditions increased the likelihood of lane changes occurring while ambient vehicles were within the simulator vehicle's blind spot. The experiment lasted 15 minutes, in accordance with Salvucci's study, allowing ample lane change maneuvers to be recorded *[10]*. After the experiment was complete, the simulator data was collected and prepared for analysis.

Experiment Design and Procedure for FCW

For the FCW application, the experiment was designed as a pre-post-test study with all participants required to drive the simulator with and without the alert message system within the developed test bed scenario. The test route consisted of a divided four lane road within urban settings with corresponding road furniture. It had a solid double yellow line down the center, solid white lines on the outside edges, dashed white lines separating the two lanes that went in each direction, and on a flat grade with a posted speed limit of 35 mph. Drives with alert messages resulted in the warning messages being generated as described under 'Design of FCW System, while drives without the alert messages did not produce any warning messages.

Thirty participants aged between 18 and 58 years of age (mean 27.3, standard deviation 8.17), consisting of 5 females and 25 males recruited from Louisiana State University's students and staff. They were all of good general health and were active drivers with a valid driver's license. They were recruited using flyers on university bulletin boards and in accordance with the university's Institutional Review Board's (IRB) standards. No financial incentive or course credit was offered so all subjects participated out of their own interest.

The effectiveness of the FCW application was tested on aggressive and conservative categories of drivers. To be able to classify the participants into aggressive and non-aggressive drivers, participants were asked to complete the Larson Driver's Stress Profile (LDSP) questionnaire but were not informed of the criteria so as to not influence the scoring of their driving behavior *[36]*. The LDSP was developed by psychiatrist Dr. John Larson for the AAA foundation for Traffic Safety and was a 40-question Likert scale instrument, grouped into four sub-groups of 10 questions each: Anger, Impatience, Competition, and Punishing Behaviors. Participants scored each question on a 0-3 scale (0 never; 1 sometimes; 2 often; 3 always). Scores were then summed up and participants with a summed score less than or equal to 21 were classified as non-aggressive drivers, while those with greater scores were classified as aggressive drivers. This criteria was selected based on previous studies by Blanchard et al. and Malta et al. *[37, 38]*. Consequently, there were 20 non-aggressive and 10 aggressive drivers from the subject pool. The validity of the LDSP questionnaire for determining aggressive and non-aggressive drivers had been thoroughly analyzed by Blanchard et al. who found the instrument to be "sound, reliable, and valid scale for use with aggressive driving."

Upon arrival at the driving simulator lab, participants were briefed on the experiment and asked to review the university's IRB approved consent sheet before signing it. This was then followed by completing the LDSP questionnaire. Participants were then asked to draw a card to determine the order of their drives (with or without alert messages). The drives were randomly determined in order to nullify any learning effect. Each participant was then allowed to practice with the driving simulator until such time that they became familiar with the controls and its operation. The actual test then followed with participants being asked to drive as they would normally on their way to work or college but to always stay in the right-lane, avoid changing lanes or overtaking, and maintain a consistent following distance that they considered as safe.

Experiment Design and Procedure for DNPW

A pilot experiment was performed to evaluate the effectiveness of the DNPW system under the limitations of the CV technology at varying MP. Twelve participants were studied to determine if the visual warning system and scenario design was sufficient for an extended study in the future. It is important to note that although the auditory warning system was developed for the future study, they were not made available for the pilot study due to some temporary limitations within the driving simulator. There were four different scenarios, including one with zero MP, one with 25% MP, one with 50% MP, and one with 75% MP. Each participant was randomly assigned two of the four scenarios, performing five overtaking maneuvers in each scenario, accounting for a total sample size of 30 maneuvers for each MP.

Unlike the naturalistic design of the BSW or FCW applications, the scenario for the DNPW pilot experiment needed to be carefully designed to assure that gaps in traffic varied. This variation in gaps ensured that both safe and unsafe gaps existed for potential overtaking maneuvers. Within the SimVista software, a two-lane two-way straight rural highway was designed specifically for overtaking maneuvers. The speed limit for the scenario was 50 mph (22.4m/s), which was obeyed by the simulated vehicles traveling in the opposing lane. Within the simulator vehicle's lane, there were five slow moving vehicles (35 mph-15.6m/s) with large gaps between each other. These vehicles presented the opportunity for the driver to perform five separate overtaking maneuvers. As the simulator vehicle approached the slow-moving vehicle in its current lane, a proximity sensor was triggered to initiate the traffic in the opposing lanes. This traffic began with a large platoon of vehicles to assure that the driver did not overtake the vehicle before vehicles in the opposing lanes were present. Following the platoon, oncoming vehicles were separated by varying headways in increments of 2s, ranging from 4s to 16s. After the final vehicle passed in the opposing lane, there was a long gap in traffic allowing the driver to overtake the vehicle with no oncoming traffic. If the driver did not overtake the slow moving vehicle before this event, the maneuver was not included in the results, but the maneuver was considered in the calculation of overtaking frequency.

Prior to the actual experiment, each participant was given the opportunity to familiarize themselves with the simulator vehicle as well as the visual warning system by practicing overtaking maneuvers within a scenario similar to the one used within the experiment. They were then given a brief opportunity to rest and fill out a demographic survey including information on their age, gender, and years of driving experience.

For the actual experiment, drivers were briefed on the experiment and randomly assigned one of the four MP scenarios. They were instructed to overtake the slow moving vehicles whenever they felt comfortable doing so. Then, the simulation was initiated and drivers underwent the approximately six-minute simulation consisting of five overtaking maneuvers. Their driving behavior was recorded and analyzed for each of the maneuvers. Next, the same process was repeated for a second randomly selected six-minute scenario at a different MP.

Following the second scenario, participants were asked to complete a post-hoc survey evaluating their opinions on the warning system. Each participant answered whether they found the visual warnings to be useful or distracting. Then they were asked if they felt more comfortable performing the passing maneuvers with the warnings. They were also asked if they felt dependent on the warnings. After these questions, they were asked whether they preferred the visual warnings, auditory, both, or neither. Similar to the BSW study, each question of the survey was answered with a "yes" or "no" to allow the researchers to statistically identify significant changes in responses between MP scenarios. The entire process for each participant lasted approximately 25 minutes.

RESULTS AND DISCUSSION

BSW Application

Data Collection and Filtering

During the BSW application experiments, data on the driving behavior and the surrounding traffic was collected. The data collected by the simulation software includes the velocity, longitudinal and lateral acceleration, throttle, braking, headway and tail way distances, lane, lane offset, and steering of the simulator vehicle. The simulation software also collected the speed of the vehicles directly ahead and behind the simulator vehicle, within its current lane. Since testing BSW only required information on lane change maneuvers, it was important to extract only the data immediately before and after the centroid of the simulator vehicle entered the adjacent lane. Similar to Salvucci's study, only data 3 sec before and after the simulator vehicle changed lanes, marking the start and end of the maneuver, were evaluated in the analysis *[10]*. To confirm that 3 sec was a sufficient duration, several pilot experiments were performed to detect the moments when noticeable changes in steering position began and ceased to occur. This collection of data was further excluded to include only the lane change maneuvers involving a vehicle approaching or within the simulator vehicle's blind spot. The remaining data was then categorized by each of the four scenarios of MPs. A summary of the lane change data is shown in Table 1.

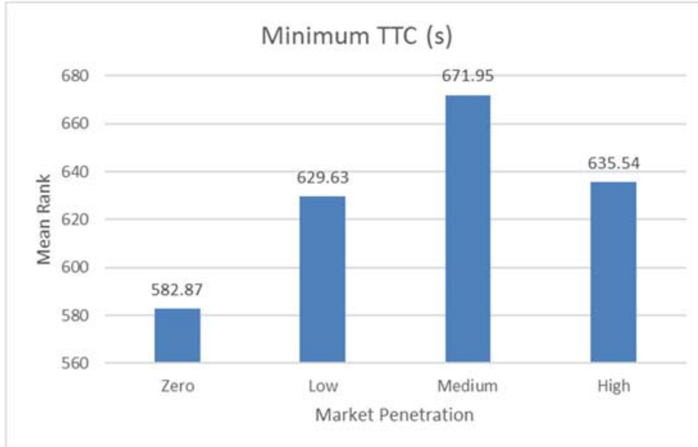
Table 1
Lane change data for each MP

Lane Change Data					
Market Penetration	Total lane changes with veh. approaching (LC)	LC per driver	LC triggering visual warnings (VW)	LC triggering VW per driver	% LC to trigger VW
Zero	279	14	0	0	0
Low	306	15	39	2.0	12.7
Medium	325	15	94	4.5	28.9
High	306	15	118	5.9	38.6

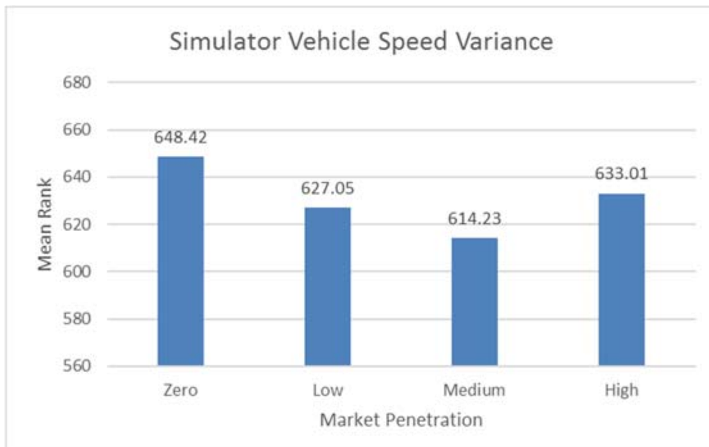
Analysis of Results

The performance measures used for the analysis of the BSW application consisted of the minimum TTC between the blind spot and simulator vehicles, the variance of the simulator vehicle's speed (σ_s^2) before and after the lane change, and the variance of the blind spot vehicle's speed (σ_b^2) immediately following the lane change maneuver. It was anticipated that the TTC could increase as the MP increased due to the improved awareness of drivers. The values of σ_b^2 were expected to decrease as the MPs increased because the driver of the simulator vehicle would be more likely to make lane change maneuvers that do not influence the blind spot vehicle. MP was expected to have little impact on σs2 because the driver would be unaware of the blind spot vehicle and unlikely to change speeds, whether the CV was present or not.

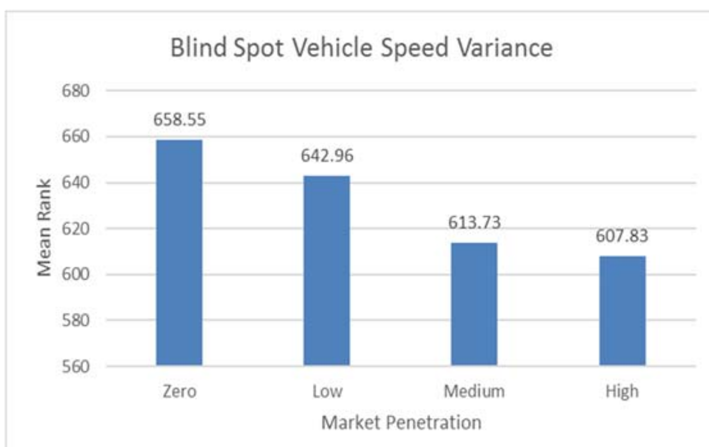
To test these hypotheses, a combination of the Kruskal-Wallis and Jonckheere-Terpstra test were used to evaluate the ranked means of the minimum TTC and variances of speeds. These non-parametric tests were used in replacement of traditional parametric ones, due to the extreme abnormality of data. In particular, a common normality, the Kolmogorov test was performed on the data set and the P-vale was < 0.001 for each measure (speed variances and minimum TTC) across all MPs, showing that the data was not normally distributed. As a result, the common parametric ANOVA tests were rejected in favor of non-parametric tests, where the analysis was performed on the rank of the data. Minimum TTC, σ_b^2, and σ_s^2 from each of the 1,216 lane changes were ranked from lowest to highest. The mean ranks of each performance measure were then calculated separately for each level of MP as seen in Figure 14. By ranking the data, outliers were positioned immediately behind the nearest value, causing them to have a minimized effect on the results *[39]*.



(a)



(b)



(c)

Figure 14

Safety parameter mean ranks for (a) minimum TTC, (b) simulator vehicle speed variance, and (c) blind spot vehicle speed variance

The Kruskal-Wallis and Jonckheere-Terpstra tests were performed on the mean ranks to investigate significant changed in safety associated with changes in MP values. To this point, the two tests were performed for each performance measure at a 90% level of confidence, with the null hypothesis that the distribution was the same across all MP. For each performance measure, the two tests were followed by a group of Dunn's Pairwise tests to determine the direction and significance of variations in mean rank, if any, across different MPs as seen in Table 2.

Table 2
Dunn's pairwise results

Kruskal-Wallis		Jonckheere-Terpstra	
Minimum TTC		Minimum TTC	
Market Penetration Sample1-Sample2	Sig.	Market Penetration Sample1-Sample2	Sig.
Zero-Low	0.110	Zero-Low	0.058
Zero-Medium	0.002	Zero-Medium	0.001
Zero-High	0.070	Zero-High	0.036
Low-Medium	0.143	Low-Medium	0.078
Low-High	0.840	Low-High	0.411
Medium-High	0.205	Medium-High	0.900
σ_b^2		σ_b^2	
Market Penetration Sample1-Sample2	Sig.	Market Penetration Sample1-Sample2	Sig.
Zero-Low	0.569	Zero-Low	0.293
Zero-Medium	0.096	Zero-Medium	0.063
Zero-High	0.062	Zero-High	0.039
Low-Medium	0.280	Low-Medium	0.160
Low-High	0.199	Low-High	0.109
Medium-High	0.826	Medium-High	0.437

The Kruskal-Wallis test results shown in Figure 15 and Table 2 confirm the assumption that MP influences the effectiveness of the BSW application. The Kruskal-Wallis test indicated that the MP significantly affected the minimum TTC between the simulator and blind spot vehicles with a p-value < 0.1. Figure 15(a) shows that the mean rank of minimum TTC generally increased as MP increased, but there was an insignificant decrease from medium to high level MP. The increase in mean rank of minimum TTC showed an increased gap between the two vehicles as MP increased, thus improving roadway safety.

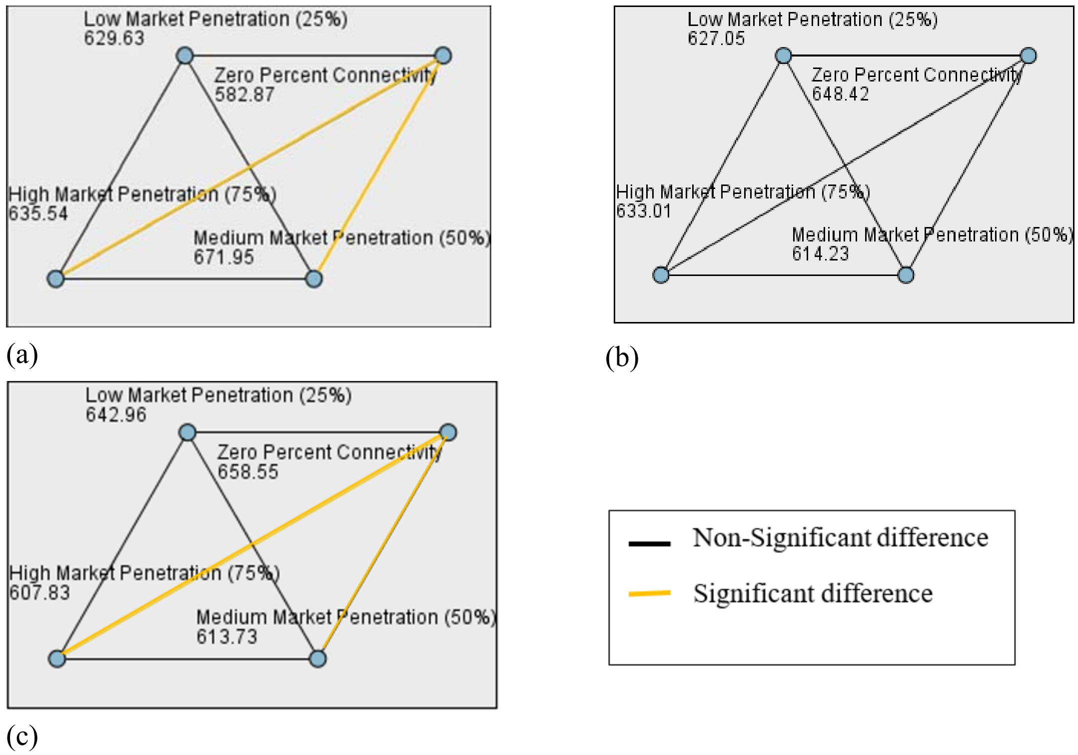


Figure 15

Kruskal-Wallis pairwise mean rank comparisons between MPs for (a) minimum TTC, (b) variance in simulator vehicle speed, and (c) variance in blind spot vehicle speed

As depicted in Table 2 and Figure 15(a), the Kruskal-Wallis pairwise results show significant increases in the mean ranks of minimum TTC from zero (582.87) to medium (671.95) MP, p = 0.002, and from zero to high (635.54) MP, p = 0.070. Despite the decrease in the TTC value from medium to high MP, this difference was not significant with a p-value = 0.205. This decrease could be associated with an increase in drivers' comfort when initiating lane change maneuvers due to the enhanced situational awareness. Since the drivers were more aware of the neighboring vehicles, they tended to accept smaller gaps for lane change maneuvers. This theory was further supported by analyzing the participants' survey responses. The responses showed that 75% of the participants with high MP and 43% of the participants with medium MP felt more comfortable performing lane changes with the visual warnings. This means that 32% more participants felt more comfortable performing lane changes as the MP increased from medium to high. To confirm the significance of the subject's increase in comfort from medium to high MPs, a two-sided t-test was performed on the percentages of participants who declared that they felt more comfortable initiating lane change maneuvers with the visual warnings. This test determined that there was a significant increase, p = 0.037, in comfort for those participants experiencing a high MP rate, thus explaining the non-significant decrease in minimum TTC. Along with analyzing the medium and high penetration rates, it is important to understand the effectiveness of the BSWs at low penetration rates. The Kruskal-Wallis pairwise results showed that there was no significant difference between mean ranks of minimum TTC for zero and low (629.63) penetration rates, $p = 0.110$. This result provided support that there must be at least a medium penetration of CVs to enhance roadway safety with the use of the BSW application.

In addition to considering the minimum TTC, σ_b^2 and σ_s^2 were examined to support the claim that MP influences the impact the CV BSW application has on roadway safety. As seen in Figure 15(b), the Kruskal-Wallis test showed no significant difference in σ_s^2 between the four MPs ($p > 0.1$). This confirms the hypothesis that MP does not affect the variance of the simulator vehicle's speed. Unlike the driver of the simulator vehicle, the blind spot vehicle was expected to react to the vehicle merging in front of it, causing an increase in σ_b^2. This was clear in the Kruskal-Wallis pairwise mean rank comparison, illustrated in Figure 15(c), which shows significant differences in mean rank for σ_b^2. Similar to the results for minimum TTC, the significant changes in σb2 do not occur until there was a medium level of MP, which provided additional support that a medium MP must exist to significantly improve the safety of the roadway. As shown in Table 2, the mean rank of σ_b^2 started to become significantly different from the zero MP scenario (658.55) at a medium level of MP (613.73) with a p-value = 0.096. To reinforce these conclusions, the Jonckheere-Terpstra test was performed on the data as well. As shown in Table 2, the test provided the same conclusions as the Kruskal-Wallis test with similar results.

FCW Application

Data Collection and Filtering

Data was collected for only when the vehicles were within 20 sec of approaching an intersection stop line due to earlier studies suggesting 15 sec as the minimum time required for drivers to react to warning messages at stop lines *[23]*. Each participant's velocity (V), lead vehicle's velocity (V_l), and headway distance (D_h) between the participant vehicle and the lead vehicle for both drives were collected at 60 Hz frequency through the proprietary software of the driving simulator. The time-to-collision for each participant (TTC_i), defined as the time in seconds for the participant's vehicle (of length l) to make contact with the lead vehicle, was calculated for each drive and for all the observations as follows:

$$TTC_i = \frac{D_h - l}{V - V_l} \quad (2)$$

For each participant, the mean value of TTC_i was then computed for each drive so that the final data consisted of one row of data for each participant containing four columns: participant ID; mean TTC for the drive with alert messages; mean TTC for the drive without alert messages; and the difference in means between the TTCs for the two drives. The data were then organized into two separate groups based on aggressive and non-aggressive drivers and analyzed separately.

Because the same participant carried out both drives, the samples were treated as dependent and subjected to a dependent t-test in ANOVA to find whether there were any differences in the driving behavior of the subjects as they were exposed to the alert messages. The paired sample test was appropriate as it did not impose an equal variance assumption on the two drives, and exclusively allots any difference between the mean TTCs for the two drives to the presence of the alert messages. Prior to the t-test, the data was checked for violation of the normality assumption. All statistical analysis were undertaken using SAS Enterprise Guide 4.3.

Analysis of Results

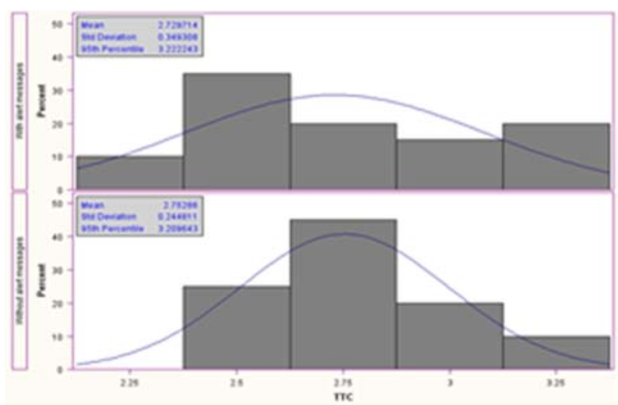
A formal test of the normality assumption was performed for the difference in means between the TTCs for the two drives for all participants. The result (Shapiro-Wilk's statistic = 0.9478, p = 0.1479) was not significant at 0.05 level of significance, and hence, the normality assumption was not rejected. This was a required assumption of the t-test for dependent samples.

The t-test for dependent samples was performed separately for the aggressive and non-aggressive drivers. The null and alternative hypotheses tested in each case were:

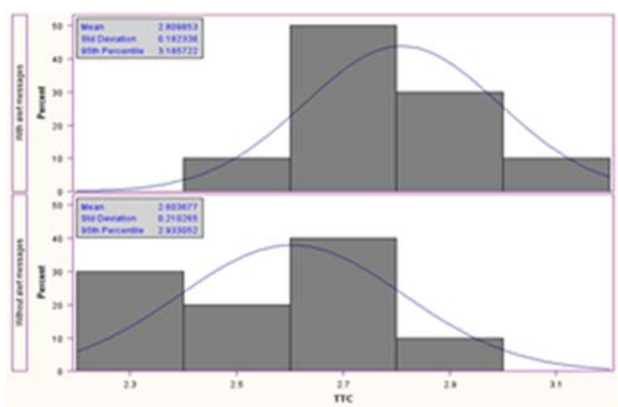
> H_0: There is no significant difference between the mean TTC observed without and with alert messages.
> H_1: There is a significant difference between the mean TTC observed without and with alert messages.

For non-aggressive drivers, the result [t (19) = -0.32, p = 0.7561] suggested that the null hypothesis cannot be rejected at a 5% level of significance. On the other hand, for aggressive drivers, the result [t (9) = 2.58, p = 0.0297] suggested that the null hypothesis can be rejected at the 5% level of significance, leading to the conclusion that that the display of alert messages caused a significant difference in the driving behavior of aggressive drivers. Furthermore, Figure 16 shows the profile plots for the two groups of drivers: TTC values for the drives with and without alert messages.

The profile plot for the non-aggressive drivers suggested that while the difference between the drives with and without alert messages was not significant, the mean TTC for the drives with alert messages was slightly lower than the drives without alert messages. This means that for drives without alert messages, the non-aggressive drivers drove with slightly more caution than they would normally do. Upon analyzing their video data, it was obvious that a few of them tended to drive closer to the lead vehicle during the drive with the alert messages. When interviewed, they expressed that they knew they would be prompted by the alert messages when they were too close to the lead vehicle and that influence their driving behavior.



(a)



(b)

Figure 16

TTC profile plot for drivers with and without alert messages, (a) non-aggressive drivers, (b) aggressive drivers

DNPW Application

Data Collection and Filtering

Data was collected for certain parameters of both the simulator vehicle and oncoming vehicle, to measure the safety benefits of the warning system. The data consisted of 30 potential overtaking maneuvers at each MP. From each potential overtake maneuver, data was collected to determine whether the participant actually chose to perform the maneuver. This information was used to calculate the overtake frequency. Data was also collected to determine whether a warning was present when the driver began the overtaking maneuver by entering the opposing lane. To help understand the warnings' influence in the drivers' decision-making process, the number of aborted maneuvers was included as well. This was considered during any situation in which the driver entered the opposing lane but did not perform the overtake maneuver. This data is included in Table 3.

Table 3
Overtaking maneuver data

Overtaking Maneuver Data					
MP	Total Overtaking Opportunities	Overtaking Frequency	Maneuvers with warning present	% Maneuvers with warning	Total Aborted maneuvers
Zero	30	22	0	0%	0
Low	30	24	4	17%	0
Medium	30	21	7	33%	0
High	30	28	17	61%	1

There were 22, 24, 21, and 28 total overtaking maneuvers for zero, low, medium, and high market penetrations respectively. There was no clear relationship between market penetration and overtaking frequency from the data in this pilot experiment. Although, it was possible that this relationship could become clear with a larger sample size. It was also recommended that drivers were provided with gaps of 18s and 20s during the future study, to increase overtake frequency. The percentage of overtake maneuvers with warnings present was proportional to the MP, showing no indication that drivers were deterred from performing overtake maneuvers while warnings were present. Also, there was only one aborted maneuver, which indicated the need for a larger sample size to draw any conclusions towards the impact of the warnings. In addition to the simulator data, the survey responses were recorded as well. The responses are shown in Table 4.

Table 4
DNPW survey results

Participant Survey				
Survey Questions	Low MP %	Medium MP %	High MP %	Total %
Visual-Useful	50%	67%	67%	61%
Visual-Distracting	0%	17%	50%	22%
Visual-Comfort	50%	67%	50%	56%
Visual-Dependent	0%	0%	17%	6%

Of the four survey questions, only one response indicated a variation between the four MP groups. It is important to note that at high levels of MP, half of the participants found the warning system to be distracting. This was not the case at low and medium MP where 0% and 17%, respectively, found the warnings to be distracting. This should be considered in the design of the warnings for the future study. From the rest of the survey, it could be gathered that the majority of participants found the warning system to be useful. They also felt more comfortable performing overtaking maneuvers with the warning system, but did not show and indication of becoming dependent on the warning messages.

Analysis of Results

To evaluate the safety of each completed overtaking maneuver during the DNPW pilot study, the TTC between the simulator vehicle and the oncoming vehicle was calculated during the initiation and termination of the maneuvers at each MPs. The initiations and terminations were considered the moments the centroid of the vehicle enters and leaves the opposing lane. It was expected that the initial TTC would be larger at higher MP with more values larger than 8s due to the drivers' increased awareness. The final TTC was also expected to increase due to the larger gaps accepted upon initiation of the maneuver. It was anticipated that fewer unsafe TTC values (less than 3s) would be collected for higher MPs.

In addition to the TTC, the time spent in the opposing lane was also considered as a safety parameter. While this parameter might not necessarily indicate a safer maneuver, it could be concluded that the less time a driver spends in the lane of the opposing traffic, the less opportunities there were for a head-to-head collision. This value might be impacted by the DNPW if the initial headway and accepted gap were affected by the warnings.

The headway between the simulator vehicle and the slow-moving vehicle in the right lane before and after the maneuver were considered as well. It was expected that drivers would allow larger headways between themselves and the vehicle ahead as MP increased, since they would be able to gain more information on the gap ahead and would not need to reduce the necessary distance to safely complete the overtake maneuver. The headway values collected included the headway at the initiation of the maneuver as well as the average headway during the 5 sec leading up to the maneuver to better understand driving behavior during the decision making process. In addition to collecting data before the maneuver, tailway time between the simulator vehicle and the slow-moving vehicle after the maneuver were collected as well to assure that the maneuver was safely completed. It was anticipated that this value would increase as MP increased, since the driver would have sufficient time to leave space between himself and the slow-moving vehicle due to the expected increase in final TTC. Table 5 summarizes the results of the pilot study by providing the mean values for each safety parameter calculated from the overtaking maneuvers for each MP.

Table 5
Overtaking maneuver safety parameters

Overtaking Maneuver Safety Parameters						
MP	Mean Initial TTC	Mean Final TTC	Mean Time in Opposing Lane	Mean Headway at Initiation of Maneuver	Mean of Average Headway 5 sec before maneuver	Tail way after Maneuver
Zero	6.22	2.94	2.92	0.37	0.94	0.62
Low	6.15	2.62	3.14	0.39	0.91	0.61
Medium	6.64	2.96	3.24	0.48	1.05	0.67
High	6.30	2.44	3.47	0.60	1.23	0.69

The mean values of each safety parameter were further illustrated in box plots to portray the effect of MP on each parameter. An ANOVA test was then performed on each parameter to determine if there were any significant difference in means between each MP. This test was performed at a confidence level of 90% similar to the BSW study. If there were significant differences, a post-hoc two-sided t-test was performed between each of the four MP groups to determine the significance between each group.

Figure 17 shows the box plot of the initial TTC between the simulator vehicle and the oncoming vehicle for each MP. While there was a slight increase in mean TTC from zero MP, 6.22s, to medium and high MP, 6.64 s and 6.3 s, respectively, this difference was not significant, $p = 0.7114$. It was possible that this was due to the small sample size of the pilot experiments. Another explanation was that the warning system does not affect the driver’s gap acceptance. This could be a cause of not trusting the warnings due to the MP of less than

100%, non-compliance with the warnings, or ineffectiveness of the warning system outside of 300 m.

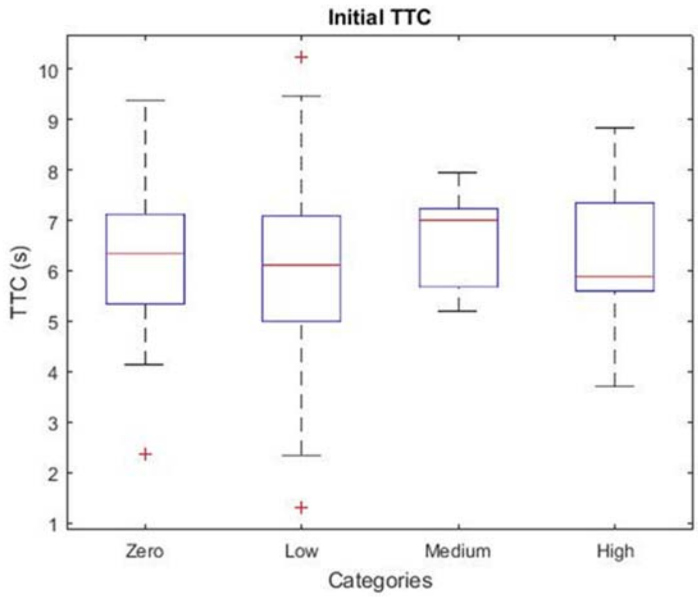


Figure 17
Initial TTC boxplot

The box plots for final TTC between the simulator vehicle and oncoming vehicle are shown in Figure 18. Similar to initial TTC, there was no significant difference in the final TTC between the levels of MP, p = 0.3074. This was likely due to the lack of significance between gap acceptances at each MP. Also note that the mean TTC for each MP was less than 3s, meaning that the majority of overtaking maneuvers were considered unsafe. It was recommended that more safe gaps of 18s and 20s be made available for the future study to allow for more safe overtaking maneuvers.

The box plots for tailway time between the simulator vehicle and the slow-moving vehicle at the end of the maneuver are shown in Figure 19. There was also a slight increase in tailway between the simulator vehicle and the slow-moving vehicle after the maneuver as the MP increases, but this change was not significant, p = 0.5683. Based on these results, it was unlikely that the warning system had any effect on the driver's tailway time at the end of the maneuver, but it was possible that some significance might be found with a larger sample.

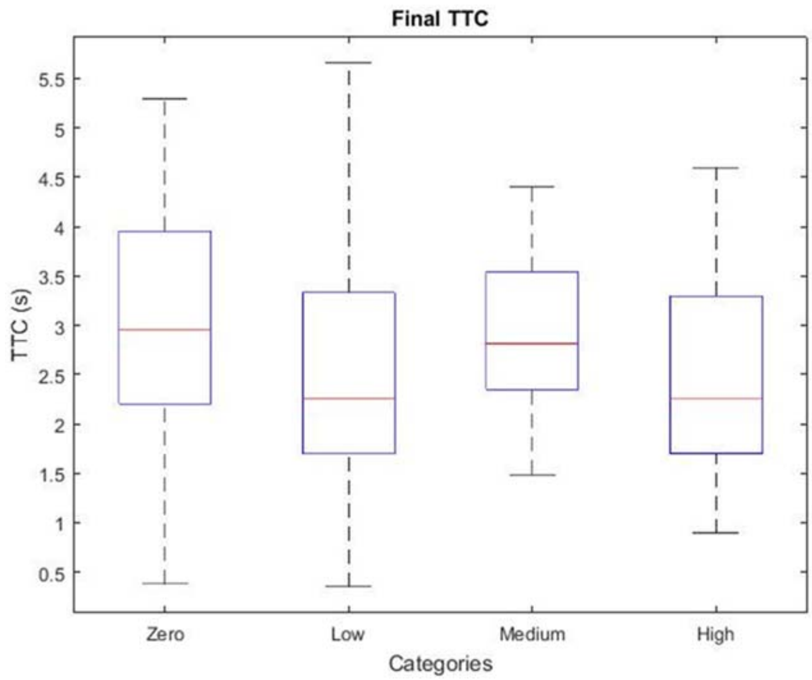


Figure 18
Final TTC boxplot

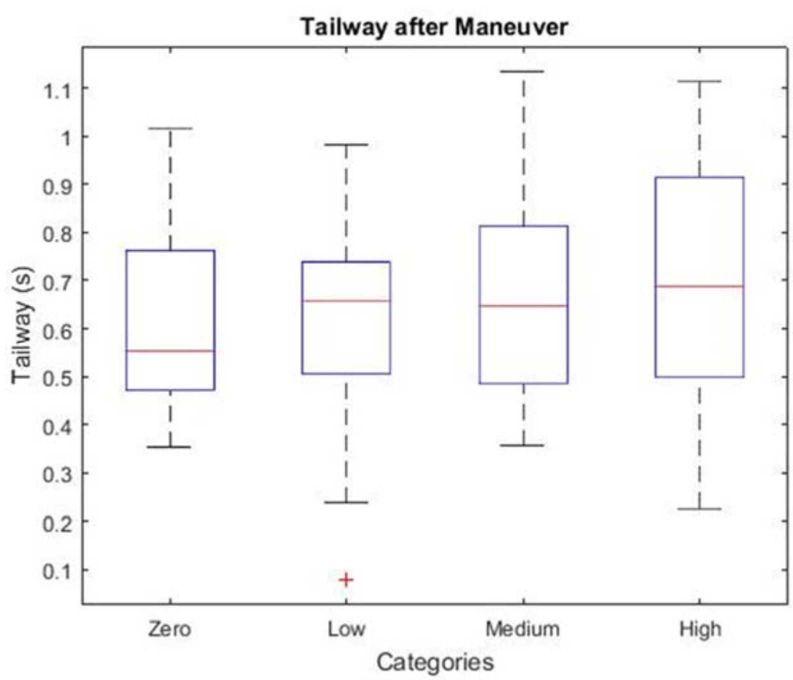


Figure 19
Box plot of tailway after the maneuver

Figure 20 illustrates the data collected for the average headways between the simulator and the slow-moving vehicle during the 5 sec leading up to the onset of the maneuver. This 5-sec period was analyzed to measure driving behavior during the decision making process. The ANOVA test found significant differences in means of the average headways during the 5 sec prior to a maneuver for each MP, $p = 0.0023$. The t-test further indicated significant differences between the means of the average headways in the zero MP scenario and the high MP scenario, $p = 0.0053$, the low and high MP scenarios, $p = 0.0031$, and the medium and high MP scenarios, $p = 0.0886$ as seen in Table 6. More specifically the average headway increased as MP increased. This indicated an increase in safety during the decision-making process. This was likely because the warning system lightens the workload of the driver during the decision-making process. Note that there was a non-significant decrease in headway from the zero MP scenario to the low MP scenario, $p > 0.1$. This may be caused by the drivers' lack of trust in the warning system at such low MP. It was recommended that this question was added to the survey of the future study.

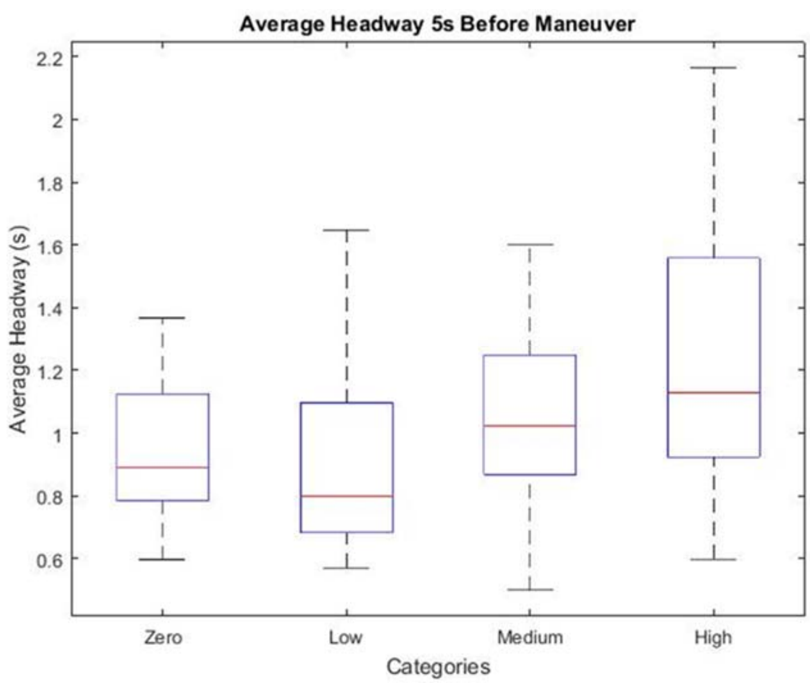


Figure 20
Box plot of average headway 5 sec prior to the maneuver

Figure 21 displays boxplot representations of the initial headway between the simulator and the slow-moving vehicle at the moment the overtaking maneuver was initiated. Similar to the average headway during the decision making process, 5 sec before the maneuver, the

ANOVA test found significant differences in the means of initial headway between the four scenarios of MP, p = 0.0084. The post-hoc t-test shown in Table 7 further indicates that there were significant differences between zero and medium MP, p = 0.0645, zero and high MP, p = 0.0073, and low and high MP, p = 0.0168. More specifically, the initial headway significantly increased at medium and high MP. This increase in headway indicated an increase in safety at the beginning of the maneuver due to the improved awareness of the driver during the decision making process.

Table 6

T-test comparisons for average headway 5 sec before maneuver

Average Headway 5 sec before the Maneuver	
Market Penetration Pairing	Significance
Zero – Low	0.6732
Zero – Medium	0.1926
Zero – High	0.0053
Low – Medium	0.1335
Low – High	0.0031
Medium – High	0.0886

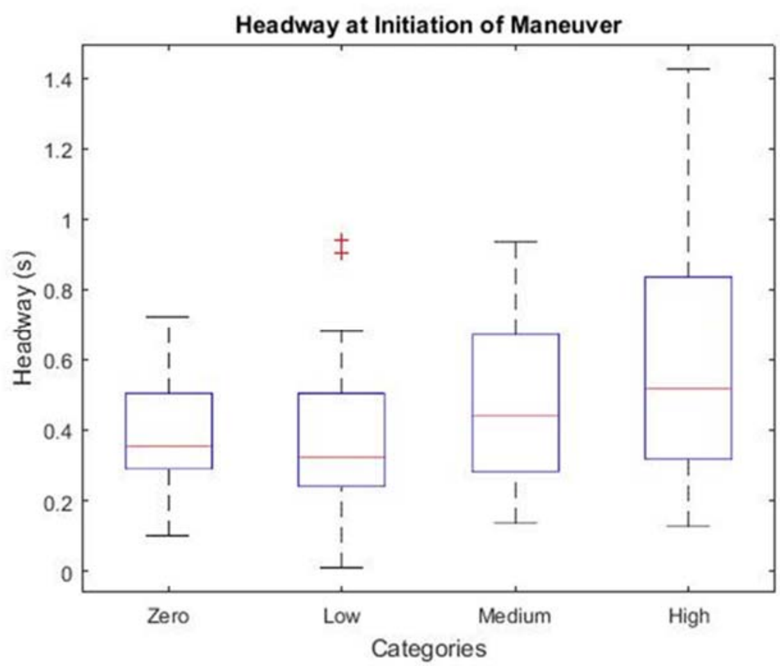


Figure 21

Box plot of headway at initiation of maneuver

Table 7
T-test comparison of headway at initiation of maneuver

Headway at Initiation of Maneuver	
Market Penetration Pairing	Significance
Zero – Low	0.7406
Zero – Medium	0.0645
Zero – High	0.0073
Low – Medium	0.1774
Low – High	0.0168
Medium – High	0.1953

Figure 22 shows a representation of the data collected for the time the simulator spent in the left lane for each maneuver at each MP. The ANOVA test indicated a significant difference in mean time spent in the opposing lane, p = 0.0886. More specifically, the t-test shown in Table 8 indicates that there were significant differences in left lane time from zero MP to medium MP, p = 0.0344, as well as from zero MP to high MP, p = 0.0148. This parameter was directly impacted by the accepted gap, and the initial headway. Since the accepted gap was similar at each MP, but the headway increased as MP increased it was expected that the time spent in the left lane could increase as the MP increased due to the extended passing zone. While this was not a clear indicator in safety, the additional time in the left lane could indicate greater opportunity for a head-to-head collision. On the other hand, the increased time spent in the opposing lane could be directly correlated to drivers being in less of a rush to complete the maneuver due to their improved awareness from the warning system.

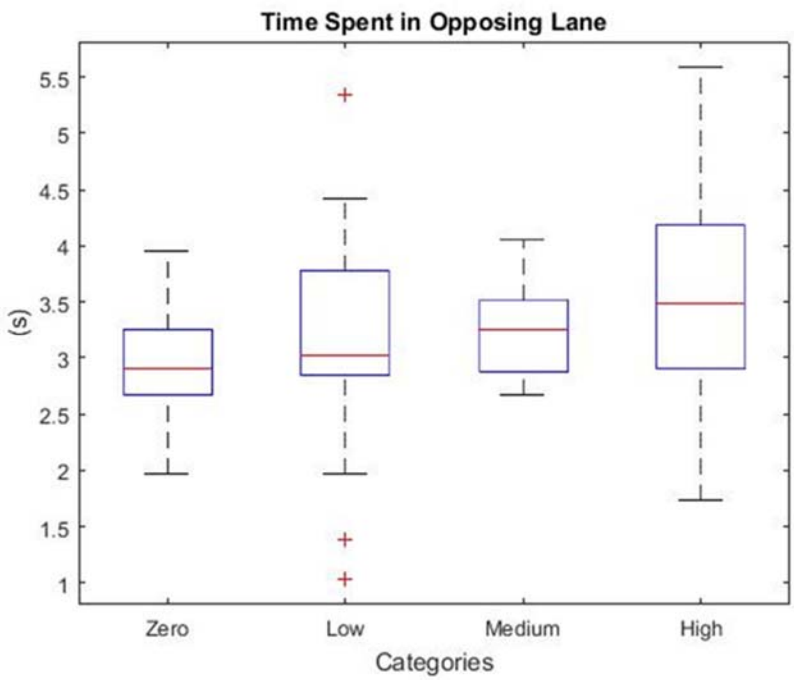


Figure 22
Box plots of time spent in opposing lane

Table 8
T-test comparison of time spent in opposing lane

Time Spent in Opposing Lane	
Market Penetration Pairing	Significance
Zero – Low	0.3712
Zero – Medium	0.0344
Zero – High	0.0148
Low – Medium	0.6502
Low – High	0.1983
Medium – High	0.2712

CONCLUSIONS

The main goal of this research was to investigate the effectiveness of three connected vehicle (CV) safety applications namely, Blind Spot Warning (BSW), Forward Collision Warning (FCW), and Do Not Pass Warning (DNPW) applications. The LSU high-fidelity driving simulator was utilized to design a CV test bed to design the three applications and tested them on volunteer drivers.

For the BSW application, the impact of market penetration levels on the effectiveness of a CV BSW application was investigated within the driving simulator. The warning system was tested on a sample of 81 participants at zero, low (25%), medium (50%), and high (75%) MPs. As drivers intended to perform lane change maneuvers with a CV in their blind spot, they received visual and auditory alerts. For each MP, data on driver behavior as well as on the surrounding traffic were collected. The data was then filtered and analyzed using two nonparametric tests paired with a posthoc pairwise test to evaluate the impact of MP on the effectiveness of the BSW application.

The results showed a significant impact of MP on the effectiveness of BSW applications. Although BSW applications in environments with low MP had no significant safety improvements to the driver, medium and high levels of MP resulted in significant safety improvements due to the additional information available to drivers in the network. The safety warnings helped to significantly increase the subject vehicle's minimum TTC during the presence of the blind spot vehicle. In doing so, the blind spot vehicle required fewer adjustments to the subject vehicle and had a significantly lower speed variance compared to the case of no warning. The results indicated that an MP around 50% was needed to effect a significant impact on this particular type of crash risk.

For the FCW application, a sample of aggressive and non-aggressive drivers was recruited and their driving performance at approaches to intersection stop lines analyzed for differences in drives with the alert messages and drives without. The performance measure used to analyze the drives was time-to-collision since the emphasis was on avoiding collisions at intersections. Upon carrying out a t-test for dependent samples for each group of drivers, the results showed that the non-aggressive drivers did not significantly change their driving behavior when exposed to the alert messages. On the other hand, aggressive drivers significantly changed their driving performance by slowing down more at intersections and increasing their time-to-collision. It was also observed that the aggressive drivers activated more alerts than the non-aggressive drivers, implying that the alert message system was successful in altering their driving style.

Finally, the DNPW application was tested in pilot experiments on 12 participants, with each of them performing two separate experiments, totaling to 24 experiments. For each experiment, participants were randomly assigned an MP of either zero, low, medium, or high, similar to the BSW study. The participants performed up to five overtaking maneuvers on a rural two-lane two-way roadway. The scenario was designed with slow moving vehicles (35 mph) in the driver's lane and oncoming traffic at varying gaps from 4-16s in the opposing lane. From each overtaking maneuver, the TTC at the beginning and end of the maneuvers was recorded, as well as the time the driver spent in the opposing lane. In addition to this, information before and after the maneuver were recorded, including the headway to the slow-moving vehicle at the initiation of the maneuver, the average headway during the decision making process before the maneuver, and the accepted tail way between the driver and the slow-moving vehicle after the maneuver.

The results did not indicate any significant differences in TTC at the beginning and end of the maneuver between each MP. This implies that a DNPW system that was limited by the abilities of CV technology and does not operate at 100% MP was not an effective means for increasing gap acceptance and avoiding dangerous overtaking maneuvers. In addition to this finding, it was also determined that there were no significant changes in a tail way after the maneuver between each MP. The warning system, however, did significantly increase the headway between the driver and the slow-moving vehicle before the maneuver. As the MP increased, the headway increased as well. Similar to the BSW, these improvements were only significant at medium and high penetration rates. This increase in headway before the maneuver suggested that drivers were able to remain more conscious of their driving behavior with the assistance of the warning system. This was an indication that this CV application was capable of improving safety during the decision-making process at medium and high penetration rates. It was also important to note that the driver spent significantly more time in the opposing lane as MP increased, but this was likely due to the increased passing distance caused by the increase in headway at the start of the maneuver.

Since the sample size was only 30 potential maneuvers per MP, this pilot investigation was limited and a future research must be conducted with a larger sample size to validate its findings. The results, though, provided insight on the benefits of a DNPW system and indicated that the method performed was an effective method for studying the effectiveness of a DNPW system.

RECOMMENDATIONS

Despite the limitations of this research, studying the BSW, FCW, and DNPW application offers an insight to sensitivity studies for CV safety applications in a simulation environment where human subjects were involved. The research also provided evidence that MP has a significant impact on the effectiveness of CV safety applications, which should be taken into consideration by consumers and manufacturers. Although MP will have a varying effect on each individual application and each application must be tested separately, this research provided evidence that CV applications only become an effective means towards improving safety when medium MP rates were met. To further assess this theory, more CV applications can be developed within the simulator environment to test their effectiveness on safety and driving behavior. More so, the impact of other factors on the safety aspect of the CV technology can be investigated using the developed test bed. More specifically, the following should be considered:

1. To explain the BSW results further, it should be considered that the experiment had limitations. The capabilities of the driving simulator is the primary limit. While the simulator environment did provide a driving experience close to the reality, the lack of 360 degrees of projection prevented the driver from looking over shoulders to observe blind spot vehicles especially in the lane change maneuvers.
2. With the successful development of the preliminary driving simulator test bed, future sensitivity tests could be undertaken to ascertain the optimal moment to activate alerts. The addition of audio prompts to the FCW and DNPW visual alerts can also be explored. Moreover, a larger sample size can be utilized to analyze demographic effects of such technology. In addition, other driving characteristics could be analyzed before and after the alert message in order to investigate potential adaptation effects in driving behavior.
3. To improve the DNPW pilot experiments, there a few changes in the scenario to be considered in the future. the limitation of the communication range are recommended to design multiple scenarios while speeds of the ambient traffic vary. This will affect the TTC threshold for the warning system, altering its potential effectiveness to improve safety. It is also recommended that more overtaking maneuvers be made available for each experiment to reduce the required sample size. To allow for additional safe overtaking opportunities it is suggested that additional gaps of 18 s and 20 s should be added. The survey results also indicated that the warning message may need to be adjusted for less distractions at higher MP. An additional survey question should be added as well to measure the participants' trust in warning systems.

ACRONYMS, ABBREVIATIONS, AND SYMBOLS

AASHTO	American Association of State Highway and Transportation Official
ADAS	Advanced Driver Assistance Systems
ATIS	Advanced Traveler Information Systems
BSW	Blind Spot Warning
CAS	Collision Avoidance Systems
CV	Connected Vehicle
DNPW	Do Not Pass Warning
DOT	Department of Transportation
DOTD	Louisiana Department of Transportation and Development
DSRC	Dedicated Short Range Communication
FCW	Forward Collision Warning
HUD	Heads-up-Display
ISWS	Inter-vehicle Safety Warning information System
IVIS	In-Vehicle Information Systems
LSU	Louisiana State University
LTRC	Louisiana Transportation Research Center
MP	Market Penetration
MUTCD	Manual on Uniform Traffic Control
NASS	National Automotive Sampling System
NHTSA	National Highway Traffic Safety Administration
PRC	Project Review Committee
TTC	Time To Collision
V2I	Vehicle To Infrastructure
V2V	Vehicle To Vehicle

REFERENCES

1. Administration, N. H. T. S. USDOT Connected Vehicle Research Program: Vehicle-to-vehicle safety application research plan. *DOT HS,* Vol. 811, 2011, p. 373.
2. *Traffic Safety Facts 2012 A Compilation of Motor Vehicle Crash Data from the Fatality Analysis Reporting System and the General Estimates System* 2012.
3. Zhao, Y., Wagh, A., Hou, Y., Hulme, K., Qiao, C., and Sadek. A.W. Integrated traffic-driving-networking simulator for the design of connected vehicle applications: eco-signal case study. *Journal of Intelligent Transportation Systems,* Vol. 20, No. 1, 2016, pp. 75-87.
4. Yan, X., Zhang, Y., and Ma, L. The influence of in-vehicle speech warning timing on drivers' collision avoidance performance at signalized intersections. *Transportation research part C: emerging technologies,* Vol. 51, 2015, pp. 231-242.
5. Yan, X., Xue, Q., Ma, L., and Xu, Y. Driving-simulator-based test on the effectiveness of auditory red-light running vehicle warning system based on time-to-collision sensor. *Sensors,* Vol. 14, No. 2, 2014, pp. 3631-3651.
6. Gertman, D. I., Spielman, Z., Brown, J., and Wold, S. Traveling to the Future: Human Factors and Ergonomics Integration, Simulation, Field Testing and Strategic Partners in Support of Heavy Vehicle Research. *Procedia Manufacturing,* Vol. 3, 2015, pp. 1366-1373.
7. Creaser, J., and Manser, M. Connected vehicles program: Driver performance and distraction evaluation for in-vehicle signing. 2012.
8. Lee, S. E., Olsen, E.C., and Wierwille, W.W. A comprehensive examination of naturalistic lane-changes.In, 2004.
9. Chen, R., Kusano, K.D., and Gabler., H.C. Driver Behavior During Lane Change from the 100-Car Naturalistic Driving Study.In *24th International Technical Conference on the Enhanced Safety of Vehicles (ESV)*, 2015.
10. Salvucci, D. D., and Liu, A. The time course of a lane change: Driver control and eye-movement behavior. *Transportation research part F: traffic psychology and behaviour,* Vol. 5, No. 2, 2002, pp. 123-132.
11. Lerner, N., Robinson, E., Singer, J., Jenness, J., Huey, R., Baldwin, C., and Fitch, G. Human factors for connected vehicles: Effective warning interface research findings.In, 2014.
12. Connected Car Forecast: Global Connected Car Market to Grow Threefold Within Five Years.In, mAutomotive, 2013. p. 8.
13. Charlton, S., Alley, B., Wigmore, B., and Baas, P. Human factors of overtaking lane design: simulator data and research findings. 2001.

14. Farah, H., Bekhor, S., and Polus, A. Risk evaluation by modeling of passing behavior on two-lane rural highways. *Accident Analysis & Prevention,* Vol. 41, No. 4, 2009, pp. 887-894.
15. Richter, T., Ruhl, S., Ortlepp, J., and Bakaba, E. Prevention of overtaking accidents on two-lane rural roads. *Transportation Research Procedia,* Vol. 14, 2016, pp. 4140-4149.
16. Hegeman, G. *Assisted overtaking: An assessment of overtaking on two-lane rural roads*. TRAIL Research School Delft, the Netherlands, 2008.
17. Shariat-Mohaymany, A., Tavakoli-Kashani, A., Nosrati, H., and Ranjbari, A. Identifying significant predictors of head-on conflicts on two-lane rural roads using inductive loop detectors data. *Traffic injury prevention,* Vol. 12, No. 6, 2011, pp. 636-641.
18. Taieb-Maimon, M., and Shinar, D. Minimum and comfortable driving headways: Reality versus perception. *Human Factors: The Journal of the Human Factors and Ergonomics Society,* Vol. 43, No. 1, 2001, pp. 159-172.
19. Ohta, H. Individual differences in driving distance headway. *Vision in vehicles,* Vol. 4, 1993, pp. 91-100.
20. Lamm, R., Psarianos, B., and Mailaender, T. *Highway design and traffic safety engineering handbook*. 1999.
21. Yang, C., and Fricker, J. Using human information processing principles to design advanced traveler information systems. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1759, 2001, pp. 1-8.
22. Lloyd, M., Bittner Jr, A., and Pierowicz, J. Driver-vehicle interface (DVI) design issues of an intersection collision avoidance (ICA) system.In *Intelligent Transportation: Realizing the Future. Abstracts of the Third World Congress on Intelligent Transport Systems*, 1996.
23. Lloyd, M., Wilson, G., Nowak, C., and Bittner, Jr., A. Brake pulsing as haptic warning for an intersection collision avoidance countermeasure. *Transportation Research Record: Journal of the Transportation Research Board*, No. 1694, 1999, pp. 34-41.
24. Fitch, G. M., Bowman, D. S., and Llaneras, E. Using wizard of oz technique to evaluate connected vehicles: distracted driver performance to multiple alerts in a multiple-conflict scenario.In *Transportation Research Board 93rd Annual Meeting*, 2014.
25. Fitch, G. M., Kiefer, R. J., Hankey, J. M., and Kleiner, B. M. Toward developing an approach for alerting drivers to the direction of a crash threat. *Human factors,* Vol. 49, No. 4, 2007, pp. 710-720.
26. Green, P. Integrated vehicle-based safety systems (IVBSS): Human factors and driver-vehicle interface (DVI) summary report. 2008.
27. Jeong, E., Oh, C., Lee, G., and Cho, H. Safety impacts of intervehicle warning information systems for moving hazards in connected vehicle environments.

Transportation Research Record: Journal of the Transportation Research Board, No. 2424, 2014, pp. 11-19.

28. Goel, S., Imielinski, T., and Ozbay, K. Ascertaining viability of WiFi based vehicle-to-vehicle network for traffic information dissemination.In *Intelligent Transportation Systems, 2004. Proceedings. The 7th International IEEE Conference on*, IEEE, 2004. pp. 1086-1091.
29. Osman, O. A., and Ishak, S. A network level connectivity robustness measure for connected vehicle environments. *Transportation research part C: emerging technologies,* Vol. 53, 2015, pp. 48-58.
30. Osman, O. A., and Ishak, S. A GA-Based Approach for Optimal Deployment of Road Side Units in Connected/Automated Vehicle Environments.In *Transportation Research Board 95th Annual Meeting*, 2016.
31. Guo, M., Ammar, M. H., and Zegura, E. W. V3: A vehicle-to-vehicle live video streaming architecture. *Pervasive and Mobile Computing,* Vol. 1, No. 4, 2005, pp. 404-424.
32. Osman, O. A., Codjoe, J., and Ishak, S. Impact of time-to-collision information on driving behavior in connected vehicle environments using a driving simulator test bed. JTLE J. *Traffic Logist. Eng,* Vol. 3, No. 1, 2015.
33. Rodriguez, J. M. Modeling the effect of Gusty Hurricane wind force on vehicles using the LSU driving simulator.In, Louisiana State University, 2014.
34. Holmes, L., Harwood, L., Klauer, S., and Doerzaph, Z. Connected vehicle systems: Evaluation of display location and application type on driving performance. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2424, 2014, pp. 39-47.
35. Winsum, W. V., and Heino, A. Choice of time-headway in car-following and the role of time-to-collision information in braking. *Ergonomics,* Vol. 39, No. 4, 1996, pp. 579-592.
36. Larson, J. A. *Steering clear of highway madness: A driver's guide to curbing stress and strain*. BookPartners, 1996.
37. Blanchard, E. B., Barton, K. A., and Malta, L. Psychometric properties of a measure of aggressive driving: The Larson Driver's Stress Profile. *Psychological Reports,* Vol. 87, No. 3, 2000, pp. 881-892.
38. Malta, L. S., Blanchard, E. B., and Freidenberg, B. M. Psychiatric and behavioral problems in aggressive drivers. *Behaviour research and therapy,* Vol. 43, No. 11, 2005, pp. 1467-1484.
39. McDonald, J. H. *Handbook of biological statistics*. Sparky House Publishing Baltimore, MD, 2009.

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