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Impact of Connected Vehicle Safety Applications on Driving Behavior at Varying Market Penetrations: A Driving Simulator Study

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IMPACT OF CONNECTED VEHICLE SAFETY APPLICATIONS ON DRIVING BEHAVIOR AT VARYING MARKET PENETRATIONS: A DRIVING SIMULATOR STUDY

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ABSTRACT

The studies conducted in this thesis evaluate the safety benefits of a blind spot warning (BSW) application and a do not pass warning (DNPW) application at low, medium, and high market penetrations (MP) of connected vehicles (CV) using a high-fidelity driving simulator. Using vehicle-to-vehicle (V2V) communication, CVs can exchange information to alert drivers of potential safety hazards and reduce potential crashes during lane change and overtaking maneuvers. A CV testbed was developed to relay visual and auditory warnings when dangerous thresholds were met for each application. 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. 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. A similar study was performed to test the DNPW application. For this pilot study, a TTC threshold was designed to warn drivers of oncoming vehicles on a two-lane two-way rural roadway. 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 both studies indicated that a medium MP (50%) is required to achieve significant safety improvement from CV safety applications.

CHAPTER 1. 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, 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 are used to detect dangerous driving scenarios and provide warning messages to the driver. These warnings are provided through the installation of CV safety applications, designed specifically for each scenario.

The effectiveness of these warning systems is dependent on the vehicle's ability to communicate with another vehicle within the designated short-range communication (DSRC) transmission range of 300m. 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.

1.1 Problem Statement

Since CV technology is not yet fully deployed, it is important to study their benefits and limitations within designed test beds. Commonly used test beds to study CV applications include test tracks, micro simulators, and driving simulators. Micro simulators, such as Paramics and Vissim, are efficient tools for studying the certain impacts of CV applications, but they are not efficient for safety studies because they do not account for the impacts of human behavior. To study how human drivers influence the effectiveness of these applications, it is important to run experiments within a test track or driving simulator. Of the two methods, driving simulators are often chosen for experimentation, due to the unsafe nature of the scenarios being studied.

The Department of Transportation has identified which of these dangerous scenarios can be improved through the use of warning systems that utilize V2V communication (*1*). The two applications this study will evaluate include a blind spot warning (BSW) application as well as a "Do not pass" warning (DNPW) system. The BSW application is designed to alert drivers of vehicles located within the driver's blind spot during lane change maneuvers. This warning system is a potential solution to reduce crashes during lane change maneuvers. This is important, because crash statistics from 2012 show that merging/lane change collisions account for 592 fatal accidents each year, 61,000 injuries, and 286,000 incidents involving property damage, which accounts for approximately 4% of all collisions (*2*). The DNPW on the other hand is designed to alert drivers of oncoming vehicles on a two-lane, two-way rural highway. This will assist drivers in performing overtaking maneuvers, which is important because passing maneuvers account for 672 fatal incidents, 19,000 injuries, and 72,000 incidents involving property damage (*2*). Although these incidents are less frequent, they create a high risk of head-to-head collisions, which can be fatal, making this scenario a primary concern.

1.2 Research Objective

To determine the safety benefits of a BSW and DNPW application, a CV network must be developed within a driving simulator test bed. Within this test bed, each application may be tested separately with human subjects to determine their effects on driving behavior. It is important to analyze human behavior because compliance to these warning systems is unlikely to occur 100 percent of the time.

In addition to analyzing driving behavior in fully connected environments, it is important to understand how drivers behave when warning messages are displayed only a portion of the time the danger of a scenario indicates they should be provided. This inconsistency in alerts is to be expected in early deployment of CV technology when MP rates remain low. This study will test the effectiveness of BSW and DNPW applications by analyzing driving behavior during dangerous maneuvers at varying MP of CV.

CHAPTER 2. LITERATURE REVIEW

2.1 Connected Vehicle Safety Applications

Since 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 testbeds to perform experimental research on the safety benefits of CV technology. There are several existing studies that assessed the safety impact of CV applications using a driving simulator (*3*-*7*). Creaser et al. (*7*) and Yan et al. (*4; 5*) performed separate studies using driving simulator based testbeds as a means to test the safety impact of CV warning systems. Creaser et al. (*7*) concentrated on alerting drivers in advance of potential risks caused by changes in roadway conditions. 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 (*5*) 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. 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. (*4*) also determined that warning messages should be provided 4.0s to 4.5s before collision.

Another simulation study by Osman et al. (*8*) used the driving simulator as a CV test bed to analyze forward collision warnings at 100% market penetration (MP) of CVs. This was achieved by enabling the lead vehicle to send safety alert messages to the simulator vehicle when certain TTC thresholds between the two vehicles were reached. The findings of this study showed a significant increase in the TTC for aggressive drivers when safety alert messages were displayed during the driving experiment. This clearly captures the anticipated safety improvements of this particular CV application.

2.2 Dangerous Lane Change Maneuvers

One CV application that is expected to improve roadway safety is the blind spot warning 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 blind spot warning 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. (*9*) and Chen et al. (*10*) used naturalistic data to analyze driving behavior during lane change maneuvers. 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 5th 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. (*11*) 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. 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 blind spot warning application, an example study was performed by the National Highway Traffic Safety Administration (NHTSA) (*12*). In this study, CV technology was utilized to design and study a blind spot warning 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. This may not be considered realistic considering the lengthy time period required to achieve this penetration rate.

Thus, it is important to examine the performance of CV applications at low and medium MPs (≤50%) which are likely to exist during the early stages of CV deployment (*13*).

2.3 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 1835ft, whereas MUTCD has set the minimum passing sight distance for marking no-passing zones at 50 mph as 800ft (*14; 15*). While these regulations do prevent dangerous maneuvers, Richter et al found that most accidents still occur where overtaking is permitted (*16*). 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 (*17*). 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 3s (*18-20*). This 3s 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 8s (*19*). This same threshold will be 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 (*20*). The findings of Taieb-Maimon and Shinar determined that the desirable headway is greater than 0.7s, while Ohita found the desirable headway to be greater than 0.6s (*21; 22*). It is important to note that these findings differ from the generally recommended 2s 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 (*23*).

For this study, TTC will be used to design the DNPW, while TTC and headway will both be 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 (*19*). The efficiency of using a warning system based on TTC is limited because the oncoming CV must also be located within the 300m DSRC range, which is not always the case at a TTC of 8s. Also, human behavior and compliance must be tested at varying levels of MP to determine if the warning system will improve safety early in deployment.

2.4 Connected Vehicle Market Penetration

Most of the past research investigating the impact of MP focused on the technology performance or the transportation network operation (*24*-*27*), rather than the effectiveness of safety applications. For instance, Goel's study (*24*) 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. The study found that an increase in MP led to a higher information propagation rate. Similarly, the study conducted by Osman and Ishak (*25*) on a network level connectivity robustness measure for CV environments also showed that the network benefits are proportional to MP. The study found that the overall robustness increases as the MP increases, 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.

This problem will be addressed in this study, where different MPs are considered for the design of a BSW and DNPW application within a driving simulator testbed. 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 lane change and overtaking maneuvers is eliminated. It is also much easier to control the driving environment throughout the various MP scenarios to be tested. Essentially, drivers are given the same opportunities to perform these 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 impact of CV market penetration on the effectiveness of a CV BSW and DNPW application to improve driving safety.

The rest of this paper provides insight on the design of the CV BSW and DNPW applications, along with the experimental procedure and results for each study. The findings and limitations of each study, as well as potential research in relation to this topic are provided at the end.

CHAPTER 3. MATERIALS AND METHODS

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 and DNPW systems.

The first study tested a warning system designed to alert drivers when CVs are present in the simulator vehicle's blind spot. The warning system was tested on a sample of 81 participants at varying CV MPs, including no CV communication, as well as low (25%), medium (50%), and high MPs (75%). Previous studies and forecasted MPs were analyzed to select these threshold values for the experiment (*13; 24; 25; 27*). The purpose of the study was to compare driving behavior under each level of MP and determine if a minimum market share is required to realize the safety benefits of CV blind spot warning applications.

The second study is a pilot study performed to analyze the safety benefits of a DNPW system, which alerts drivers of oncoming traffic on a two-way two-lane rural road. The study was performed on a sample of 12 participants, who each performed two separate experiments, totaling to 24 experiments. These experiments were tested at zero, low, medium, and high MP as well. The methodology used to perform the proposed research is thoroughly discussed in the following sections.

3.1 Driving Simulator Testbed

The driving simulator at Louisiana State University has been used for research studies in the field of transportation engineering (*8; 28*). Recently an emphasis has been made to develop studies that incorporate CV applications into the simulator environment. The CV testbed has the ability to collect information through V2V communication and project messages, warning the simulator participant of various driving hazards.

As shown in FIGURE 1, the simulator consists 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 produces forward and backward motion when the driver applies the brakes or throttle. The driving simulator utilizes automated sensing devices to gather data including engine RPM, heading error, vehicle speed, acceleration, trajectory offset, braking, and vehicle position. Four cameras are built into the vehicle to capture footage of the driver, which can be used to analyze participant's behavior and reactions. The virtual environment is created using SimVista software and the vehicle simulation is run using the SimCreator software. Simulation sound is also produced to simulate engine sound, tire sound, and noise from the vehicle.

FIGURE 1 Louisiana State University driving simulator.

3.2 Connected Vehicle Testbed

The test bed developed for the previous study (*8*) was improved to simulate a more realistic and adaptable CV network. The improved test bed consists of the LSU driving simulator vehicle, along with fifty-two simulated vehicles in the ambient traffic that are generated randomly within an urban environment. The vehicles are generated with a randomly assigned unique ID, which classifies their type as either a connected or a non-connected vehicle. To simulate the various levels of MP, a pre-established connectivity ratio is set and assigned to the random vehicle generator. After the vehicles are assigned an ID and labeled as connected or non-connected vehicles, their current lane is identified.

Based on the location, lane and connectivity of the ambient vehicles, the communication process can begin. The simulator vehicle then starts to collect information about the ambient traffic that replicates what would be available in probe data messages. Such information is transmitted by neighboring CVs simultaneously within the designated short-range communication (DSRC) transmission range of 300m. To begin the communication process, the simulator vehicle collects information from the vehicles located ahead and behind. From these CVs the closest CVs in any lane are located and communication between these vehicles occur. Next, the vehicles ahead and behind are located again and communication continues. This process repeats itself and these CVs are able to transmit these messages to other neighboring CVs, until there is no longer a new CV in range, as seen in FIGURE 2.

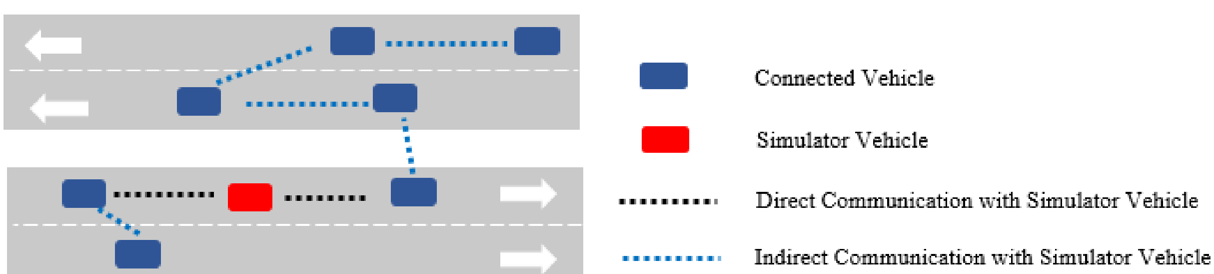


FIGURE 2 Simulated connected vehicle communication network.

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

3.3 Blind Spot Warning Application

3.3.1 Development of the Blind Spot Warning Application

This study uses the testbed to locate CVs within the simulator vehicle's blind spot and provide the driver with visual and auditory warnings as he or she intends to perform a lane change maneuver. Although the information from vehicles traveling in the opposite direction are 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 3 illustrates this process of gathering information and providing blind spot warnings.

To obtain the necessary information for the visual warnings, the CVs in the neighboring lane to the simulator vehicle are 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 is located, a series of requirements must be met to trigger a visual response warning. First, it is determined whether the nearby vehicle is located behind the simulator vehicle, within the bearings of 91-179 degrees (right) or 181-269 degrees (left). These bearing values are determined based on data collected from the test bed to determine where vehicles behind the simulator vehicle can be located. If the vehicle is approaching the simulator vehicle's blind spot (within 30m in the adjacent lane) and driving in the same direction as the simulator vehicle, an orange visual warning is displayed on the bottom center of the front windshield. The distance of 30m is determined such that a warning is established within a safety threshold before the approaching vehicles fall within the simulator vehicle's blind spot and was determined through several pilot tests within the simulator. This warning is established whether the simulator vehicle's driver intends to change lanes or not and remains on display until the visual blind spot warning requirements are no longer met.

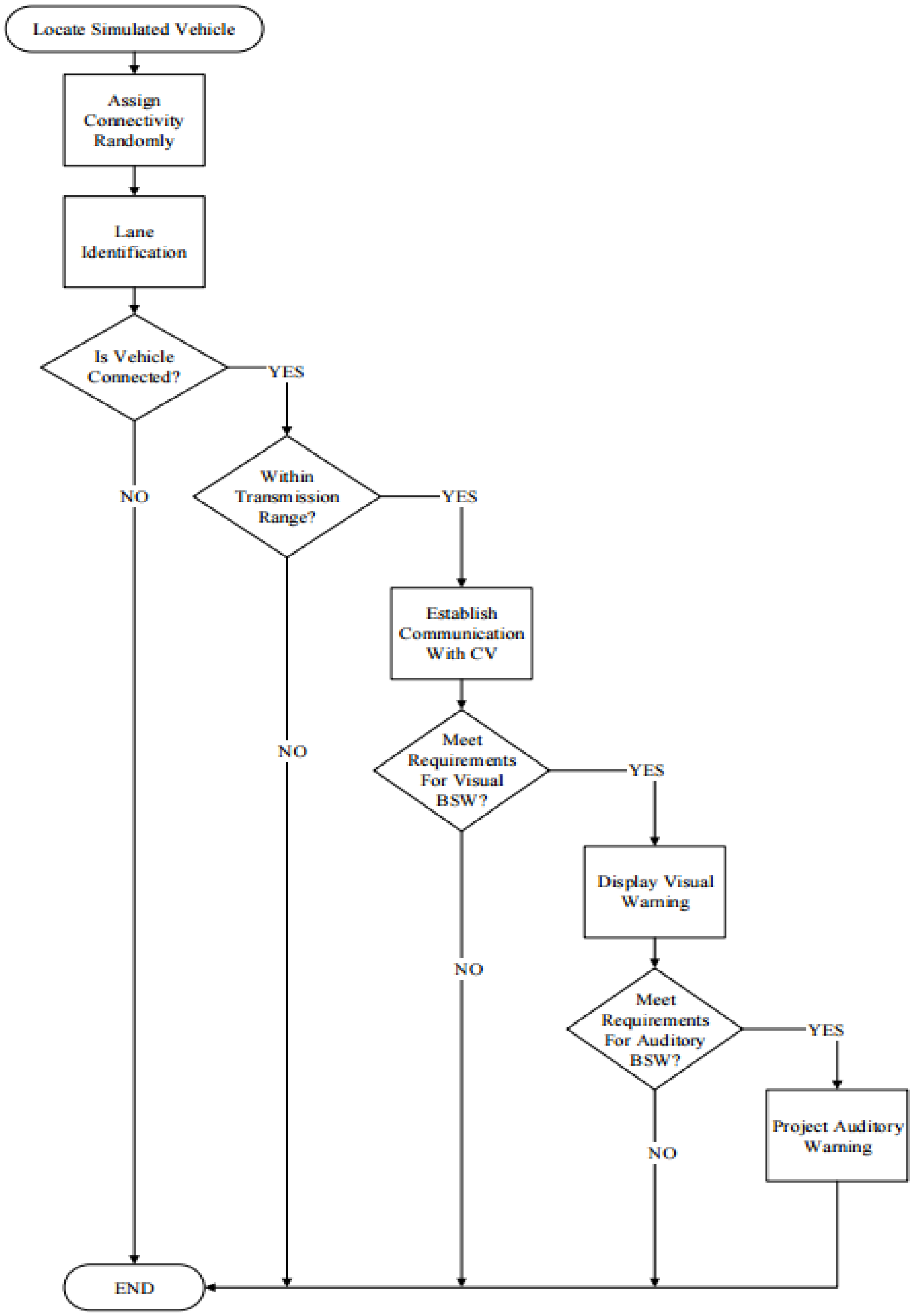


FIGURE 3 Blind spot warning (BSW) calling process.

The warning states "Vehicle passing on the right" if the vehicle is to the right, and "Vehicle passing on the left" if the vehicle is to the left as seen in FIGURE 4. The location of the visual warning was chosen to imitate a head-up display, as identified in the previous study (*8*).

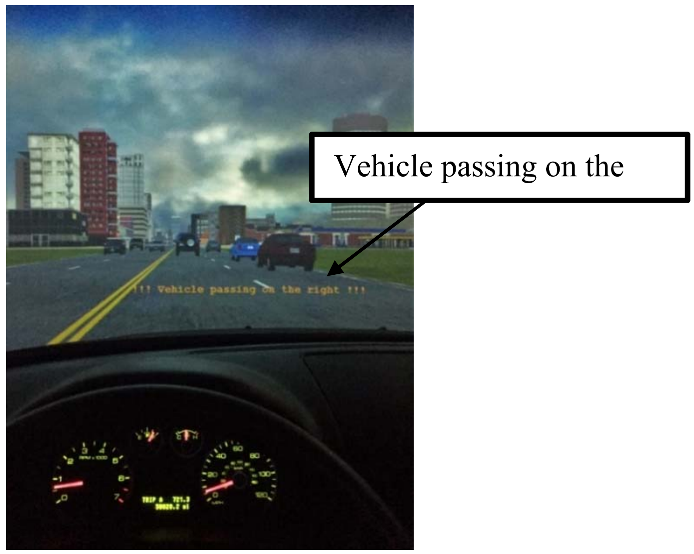


FIGURE 4 Visual blind spot warning.

In addition to the visual warning, an auditory warning is provided if the driver attempts a lane change maneuver while a CV occupies the simulator vehicle's blind spot. The distance set to trigger the auditory warning is reduced to 15m behind the simulator vehicle. This distance is determined based on several pilot tests performed to design a blind spot within the simulator environment. Since the driving simulator lacks 360 degrees of vision, a blind spot is simulated by establishing a location in which the approaching vehicle is not visible within the side mirrors of the simulator vehicle. The distance also accounts for a safety cushion to ensure the driver has enough time to cancel their lane change maneuver as a vehicle is entering the driver's blind spot.

Since not all drivers tend to use turn signals, vehicle dynamics were used to identify attempted lane change maneuvers rather than the activation of a turn signal. The used vehicle dynamics include throttle, speed, lane offset, and steering. The driver must steer greater than 15 degrees in the direction of the passing vehicle and the simulator vehicle must 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 must be either moving at a speed greater than 4.47m/s (10 mph) or have a throttle position greater than 0.1 to prevent false readings while the vehicle is 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 are met as well as the requirements for the visual warnings, a loud alarm will sound off on the simulator vehicle's speaker to alert the driver of a vehicle in the blind spot. FIGURE 5 displays the positional requirements to trigger the auditory and visual blind spot warnings.

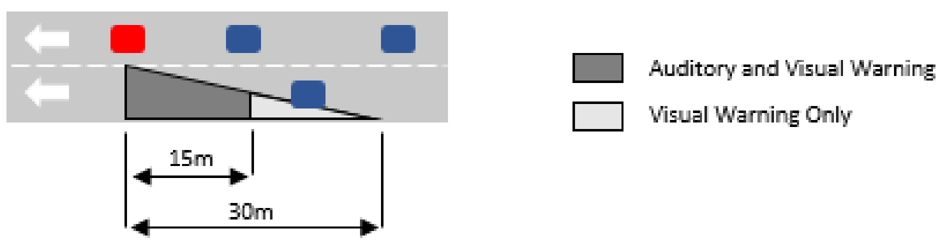


FIGURE 5 Maximum range to trigger visual and auditory blind spot warnings.

3.3.2 Experiment Design and Procedure

A sample of 90 participants, ranging in age from 19 to 53, including 58 males and 32 females, were recruited to participate in the study. 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 demographic information collected for each participant is further displayed in TABLE 1. The subjects' driving behavior was observed during lane change maneuvers, with and without the assistance of CV blind spot warnings. These visual and auditory blind spot warnings were provided using V2V communication at varying levels of MP for CVs.

TABLE 1 BSW study sample demographic survey.

Market Penetration	Age		Gender		Years With License	
	Mean	St. dev.	M	F	Mean	St. dev.
Zero	27.50	8.9135	15	5	11.15	9.1943
Low	25.30	6.1923	11	9	7.80	6.0548
Medium	23.71	4.4949	14	7	6.81	4.5316
High	28.20	8.0846	13	7	11.00	7.7717

To begin each experiment, participants were randomly assigned one of the four market penetrations. Twenty participants were assigned to scenarios with zero, low, and high MP levels and twenty-one 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 may 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 study, 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 blind spot warnings.

Next, the participants were briefed on the study and given instructions on how to operate the driving simulator vehicle. They were shown an example of the blind spot warnings 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. The drivers were then instructed to perform frequent lane change maneuvers 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 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 the 15-minute experiment within the driving simulator. For the experiment, the subjects drove throughout a 4 lane arterial highway within an urban environment. The fixed driving scenario consists 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 (*11*). After the experiment was complete, the simulator data was collected and prepared for the analysis.

3.3.3 Data Collection and Filtering

Immediately after the test, the participants were asked to fill out a brief opinion survey on the visual and auditory blind spot warnings. Each question of the survey was answered with a "yes" or "no," in lieu of the Likert scale survey, to allow the researchers to statistically identify significant changes in responses between MP scenarios. The participants were first asked whether they found the visual warnings useful or distracting. Then, they were asked if they felt dependent on the visual warnings, and if they felt more comfortable performing lane change maneuvers with them. The same questions were asked for the auditory warnings. Following these questions, they were asked if they would rather have both warnings, neither, only visual, or only auditory. Lastly, they were asked whether they suffered from motion sickness during the experiment, and they were given the opportunity to make comments on the test as a whole. The percentage of participants answering "yes" to each survey question are shown in TABLE 2.

From the survey results, two questions returned a significant difference in responses between the MP. Drivers became more comfortable performing lane-change maneuvers as MP increased from medium to high rates for both the visual and auditory warnings. From the other survey responses, it can be gathered that the majority of participants find the visual warnings to be useful and few participants found the warnings to be distracting. Very few drivers felt dependent on the warnings, but the majority of participants felt more comfortable with the visual warnings. When asked for their preference in warning system, significantly more users found the visual warnings to be preferred over the auditory warnings.

TABLE 2 Post-hoc participant survey results.

Participant Survey				
Survey Questions	Low MP	Medium MP	High MP	Total
Visual-Useful	70%	76%	60%	69%
Visual-Distracting	35%	10%	15%	20%
Visual-Dependent	5%	5%	10%	7%
Visual-Comfortable	65%	43%	75%	61%
Auditory-Useful	60%	29%	50%	46%
Auditory-Distracting	20%	38%	30%	30%
Auditory-Dependent	0%	5%	5%	3%
Auditory-Comfortable	50%	24%	40%	38%
Preference-Visual	40%	48%	55%	48%
Preference-Auditory	20%	24%	15%	20%
Preference-Both	25%	10%	15%	16%
Preference-Neither	10%	19%	15%	15%

In addition to the survey, 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 this study 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 three seconds before and after the simulator vehicle changed lanes, marking the start and ends of the maneuver, were evaluated in the analysis (*11*). To confirm that three seconds 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 3.

TABLE 3 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%

After processing the data, the filtered data was used in the analysis to evaluate the performance measures of the simulator vehicle and blind spot vehicle during lane change maneuvers. The speed of the blind spot vehicle was evaluated to quantify the adjustments executed by the simulated vehicle due to the simulator vehicle's lane change maneuver. Minimum TTC and variances of speed were calculated to quantify the safety of lane change maneuvers at varying MPs of CVs equipped with a blind spot warning application. Minimum TTC was chosen as a safety parameter to measure the crash risk between the simulator vehicle and the blind spot vehicle. It is important to note that although there were 81 participants in the study, the actual sample size used to evaluate each performance measure was the total number of lane changes with a vehicle approaching or within the simulator vehicle's blind spot, as seen in TABLE 3.

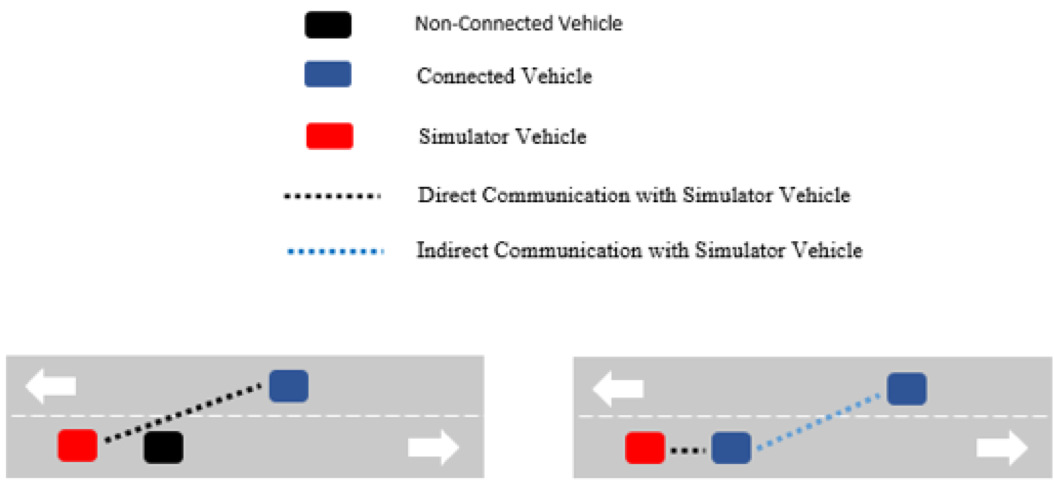
3.4 Do Not Pass Warning Application

3.4.1 Development of the Do Not Pass Warning Application

For a subsequent pilot study on a DNPW CV application, the CV testbed was adapted to warn drivers of oncoming traffic prior to an overtaking maneuver. This warning system was applied within the same CV network designed for the BSW study. In a similar method to the previous study, the application is designed to collect information from nearby CVs within the DSRC transmission range through probe data messages as seen in FIGURE 6. By filtering through these probe data messages, the application is able to gather the speed and location of oncoming vehicles if they are also equipped with CV technology. This communication can occur directly between the oncoming CV and the simulator vehicle as seen in FIGURE 6(a), but sometimes indirect communication shown in FIGURE 6(b) can be more efficient. By sending information indirectly from the oncoming CV to the CV ahead of the simulator, the range of the communication network can be extended further than 300m. This allows for warning messages to be displayed to the driver even when the oncoming CV is located further than 300m from the simulator vehicle. By comparing the speed and location of the oncoming CV to that of the simulator vehicle, the TTC between each may be calculated using Equation (1).

$$TTC = (x_s - x_o) \div (v_s - v_o) \tag{1}$$

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



(a) (b)

FIGURE 6 CV communication network (a) using direct and (b) indirect communication.

If the TTC value is less than the minimum safe threshold of 8s, a visual warning is displayed on the dashboard of the simulator vehicle stating "Do Not Pass," as seen in FIGURE 7. It is important to note that this warning system is limited by the abilities of the CV technology. Since the communication range is only 300m, the maximum TTC value required to display a warning to the driver is dependent on the speed of both the simulator and simulated vehicles. Since the speed limit on the roadway for this study is 50mph (22.352 m/s), Equation (1) determines that the warning will only appear when the TTC is less than 6.7s if both the simulator vehicle and simulated vehicle are traveling the speed limit. This threshold varies as the simulator vehicle and oncoming vehicle adjust their speeds. FIGURE 8 shows the scenario in which a visual DNPW will be displayed. It is also important to note that for this application to function in the real world upon deployment, a condition must also be met that the road is a two-way two-lane roadway. To detect whether this roadway condition exists, vehicle-to-infrastructure (V2I) communication must occur or GPS systems must be implemented within the equipped vehicle.

FIGURE 7 Visual DNPW screenshot.

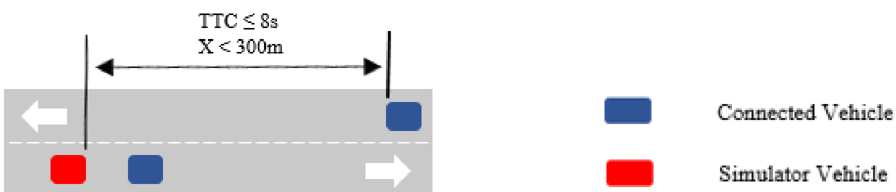


FIGURE 8 DNPW scenario.

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, are applied to this application as well to detect an attempted overtake maneuver. FIGURE 9 displays the DNPW calling process.

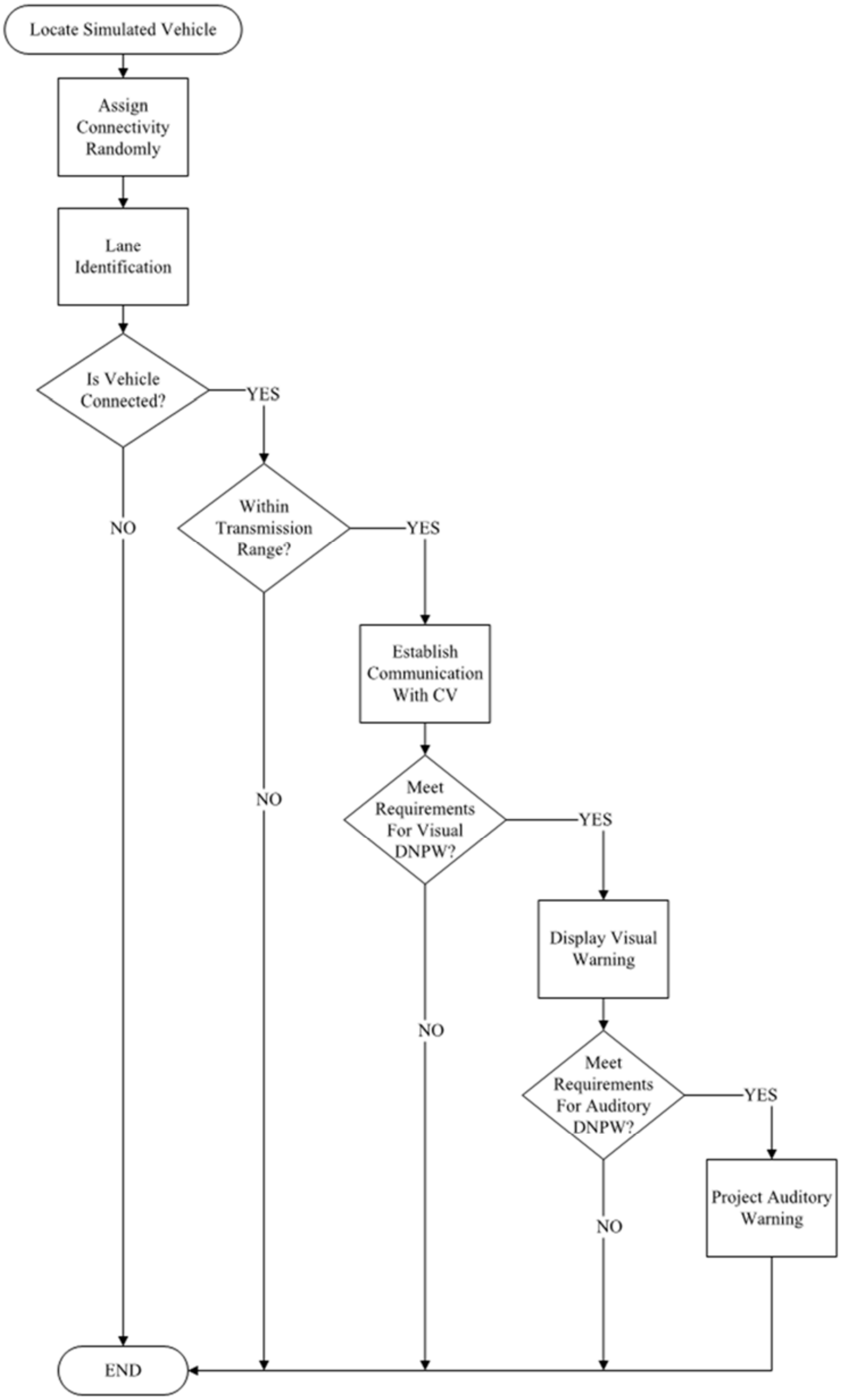


FIGURE 9 DNPW calling process.

3.4.2 Pilot Study Design and Procedure

A pilot study 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. A summary of the demographic characteristics of the sample is shown in TABLE 4.

TABLE 4 DNPW pilot study sample demographic survey.

Market Penetration	Age		Gender		Years With License	
	Mean	St. dev.	M	F	Mean	St. dev.
Zero	27.67	8.7305	5	1	11.00	8.9629
Low	22.17	2.0344	3	3	6.17	2.1148
Medium	27.50	8.8459	3	3	10.83	9.0631
High	21.50	1.8028	3	3	5.67	2.0548

Unlike the naturalistic design of the BSW study, the scenario for the DNPW pilot study 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, which was obeyed by the simulated vehicles traveling in the opposing lane. Within the simulator vehicle's lane, there were five slow moving vehicles (35mph) 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 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 feel 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 the felt dependent on the warnings. 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.

3.4.3 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 any situation in which the driver entered the opposing lane but did not perform the overtake maneuver. This data is included in TABLE 5.

There were 22, 24, 21, and 28 total overtaking maneuvers for zero, low, medium, and high market penetrations respectively. There is no clear relationship between market penetration and overtaking frequency from the data in this pilot study. Although, it is possible that this relationship will become clear with a larger sample size. It is also recommended that drivers are provided with gaps of 18s and 20s during the future study, to increase overtake frequency. The percentage of overtake maneuvers with warnings present is proportional to the MP, showing no indication that drivers were deterred from performing overtake maneuvers while warnings are 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 6.

TABLE 5 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	32%	0
High	30	28	17	61%	1

TABLE 6 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%

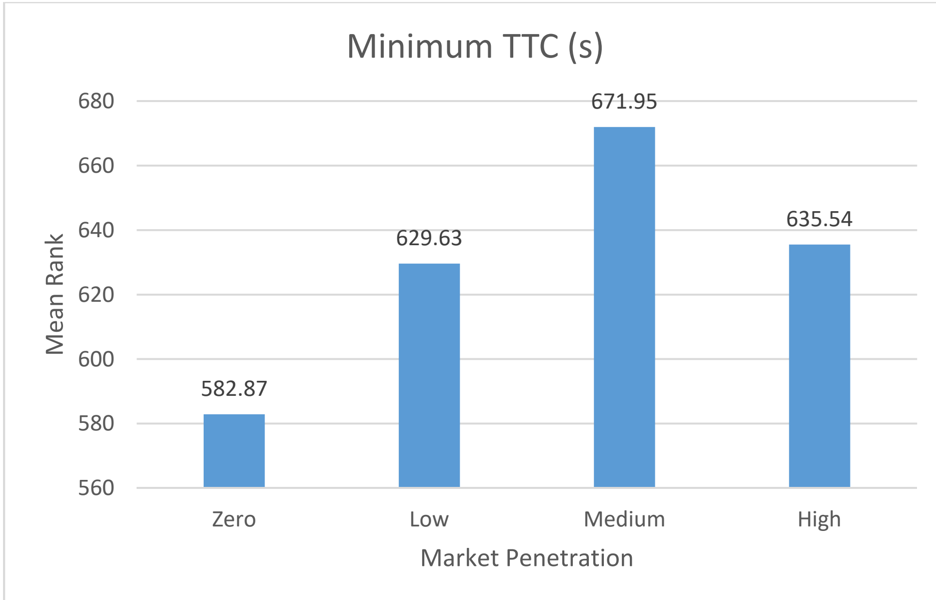
Of the four survey questions, only one response indicated a variation between the four MP groups. It is important to note that at high levels of MP, half of the participants found the warning system to be distracting. This was not the case at low and medium MP where 0% and 17% respectively found the warnings to be distracting. This result may be caused by the low sample size. Nonetheless, this should be considered in the design of the warnings for the future study. Steps should be taken to assure that the warning system is less distracting to drivers at higher MPs. From the rest of the survey, it can 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 an indication of becoming dependent on the warning messages.

CHAPTER 4. RESULTS AND DISCUSSION

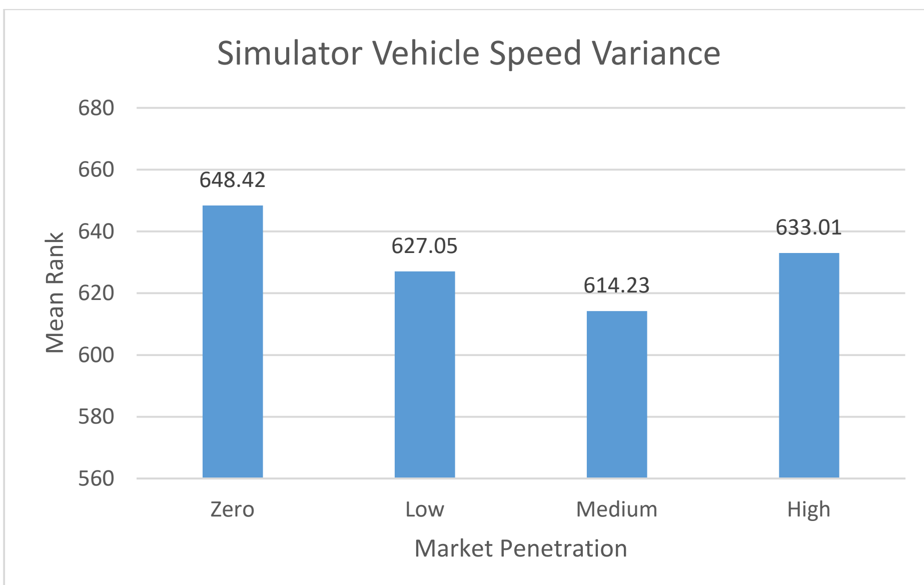
4.1 Blind Spot Warning Application

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 would increase as the MP increased due to the improved awareness of the driver. 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 σ_s^2 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, 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 is 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 10. By ranking the data, outliers were positioned immediately behind the nearest value, causing them to have a minimized effect on the results (*29*).



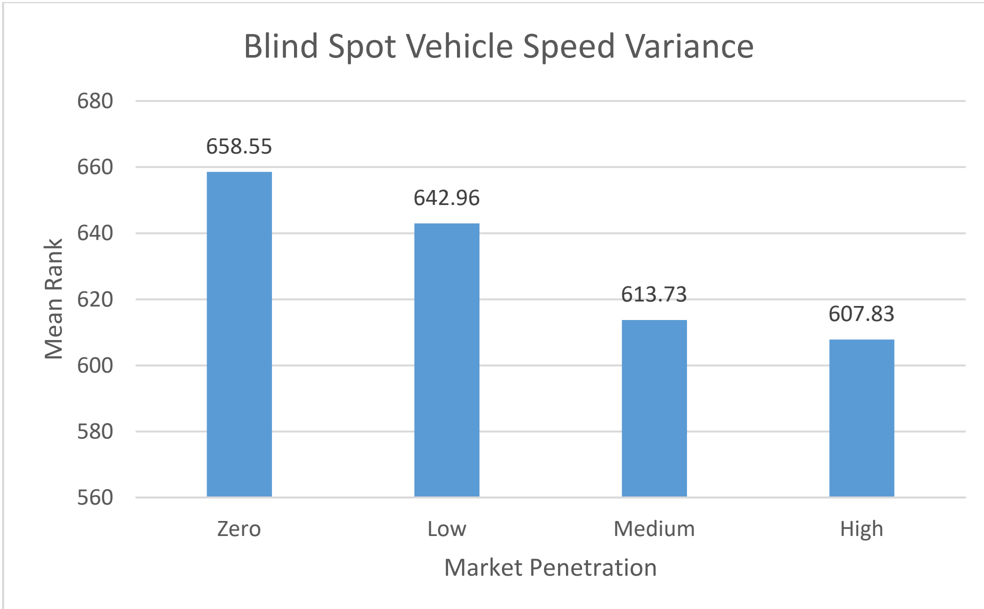
(a)



(b)

FIGURE 10 Safety parameter mean ranks for (a) minimum TTC, (b) simulator vehicle speed variance, and (c) blind spot vehicle speed variance.

(FIGURE 10 continued).



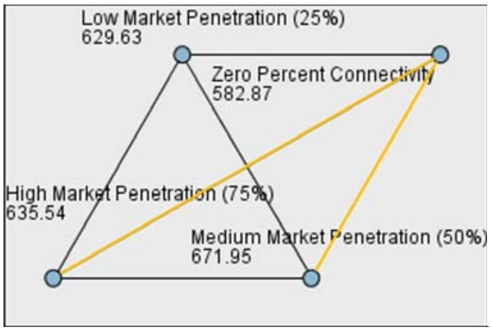
(c)

The Kruskal-Wallis and Jonckheere-Terpstra tests were performed on the mean ranks to investigate significant changes 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 7.

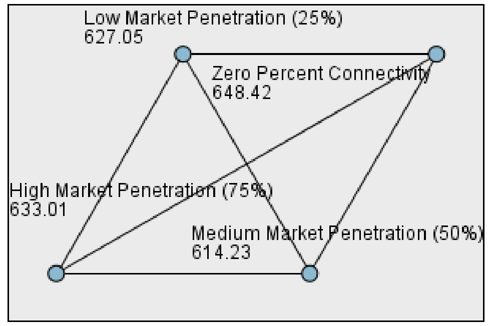
The Kruskal-Wallis test results shown in FIGURE 11 and TABLE 7 confirm the assumption that MP influences the effectiveness of the blind spot warning application. The Kruskal-Wallis test indicates that the MP significantly affected the minimum TTC between the simulator and blind spot vehicles with a p-value < 0.1. FIGURE 11(a) shows that the mean rank of minimum TTC generally increases as MP increases, but there is an insignificant decrease from medium to high level MP. The increase in mean rank of minimum TTC shows an increased gap between the two vehicles as MP increases, thus improving roadway safety.

TABLE 7 Dunn's pairwise results.

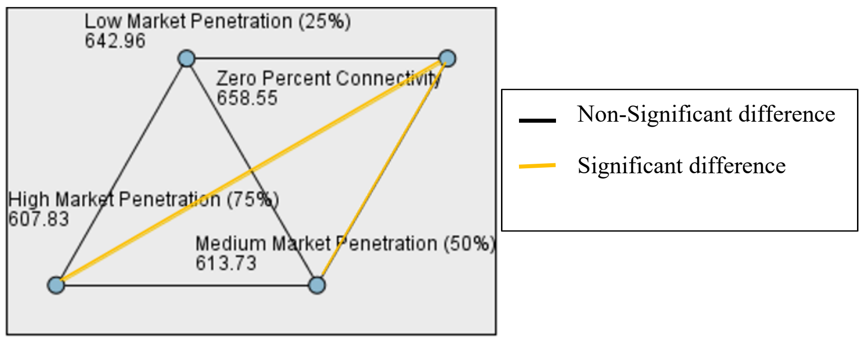
Kruskal-Wallis		Jonckheere-Terpstra	
Minimum TTC		Minimum TTC	
Market Penetration Sample1-Sample2	Sig.	Market Penetration Sample1-Sample2	Sig.
Zero-Low	0.110	Zero-Low	0.058
Zero-High	0.070	Zero-High	0.036
Zero-Medium	0.002	Zero-Medium	0.001
Low-High	0.840	Low-High	0.411
Low-Medium	0.143	Low-Medium	0.078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



(a)



(b)



(c)

FIGURE 11 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 7 and FIGURE 11(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 is not significant with a p-value = 0.205. This decrease can be associated with an increase in drivers' comfort when initiating lane change maneuvers due to the enhanced situational awareness. Since the drivers are more aware of the neighboring vehicles, they tend to accept smaller gaps for lane change maneuvers. This theory is 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 is 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 blind spot warnings at low penetration rates. The Kruskal-Wallis pairwise results show that there is no significant difference between mean ranks of minimum TTC for zero and low (629.63) penetration rates, $p = 0.110$. This result provides support that there must be at least a medium penetration of CVs to enhance roadway safety with the use of the blind spot warning 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 blind spot warning application has on roadway safety. As seen in FIGURE 11(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 is expected to react to the vehicle merging in front of it, causing an increase in σ_b^2. This is clear in Kruskal-Wallis pairwise mean rank comparison, illustrated in FIGURE 11(c), which shows significant differences in mean rank for σ_b^2. Similar to the results for minimum TTC, the significant changes in σ_b^2 do not occur until there is a medium level of MP, which provides additional support that a medium MP must exist to significantly improve the safety of the roadway.

As shown in TABLE 7, the mean rank of σ_b^2 starts 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 7 the test provided the same conclusions as the Kruskal-Wallis test, with similar results.

4.2 Do Not Pass Warning Application Pilot Study

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 MP. 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 may not necessarily indicate a safer maneuver, it can be concluded that the less time a driver spends in the lane of the opposing traffic, the less opportunities there are for a head-to-head collision. This value may be impacted by the DNPW if the initial headway and accepted gap are 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 5s 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 8 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 8 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 5s before maneuver	Tailway 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 are 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 4 MP groups to determine the significance between each group.

FIGURE 12 shows the box plot of the initial TTC between the simulator vehicle and the oncoming vehicle for each MP. While there is a slight increase in mean TTC from zero MP, 6.22s, to medium and high MP, 6.64s and 6.3s respectively, this difference is not significant, $p = 0.7114$. It is possible that this is due to the small sample size of the pilot study. Another explanation is 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 300m.

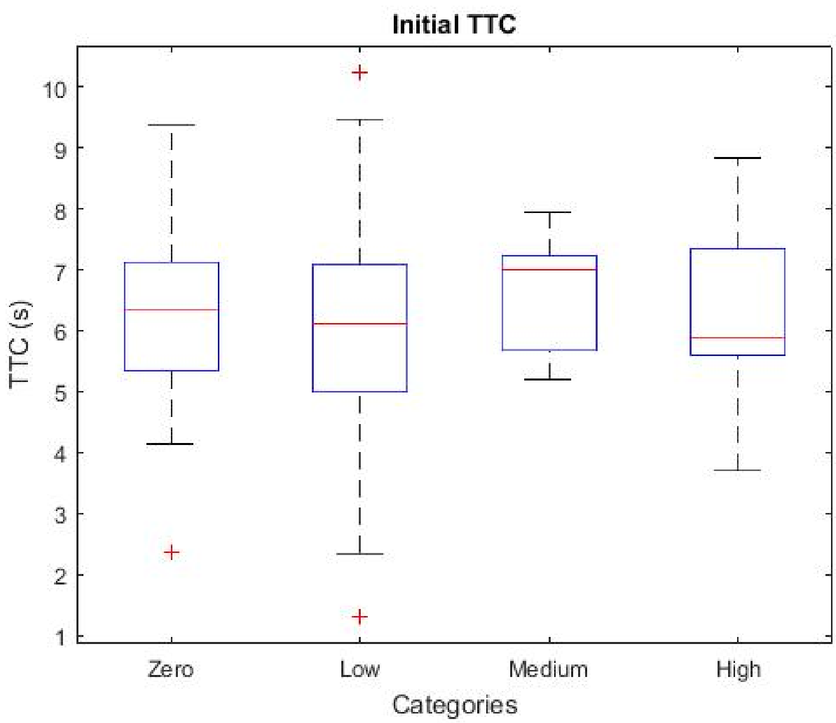


FIGURE 12 Initial TTC boxplot.

The box plots for final TTC between the simulator vehicle and oncoming vehicle are shown in FIGURE 13. Similar to initial TTC, there is no significant difference in final TTC between the levels of MP, $p = 0.3074$. This is 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 is recommended that more safe gaps of 18s and 20s be made available for the future study to allow for more safe overtaking maneuvers.

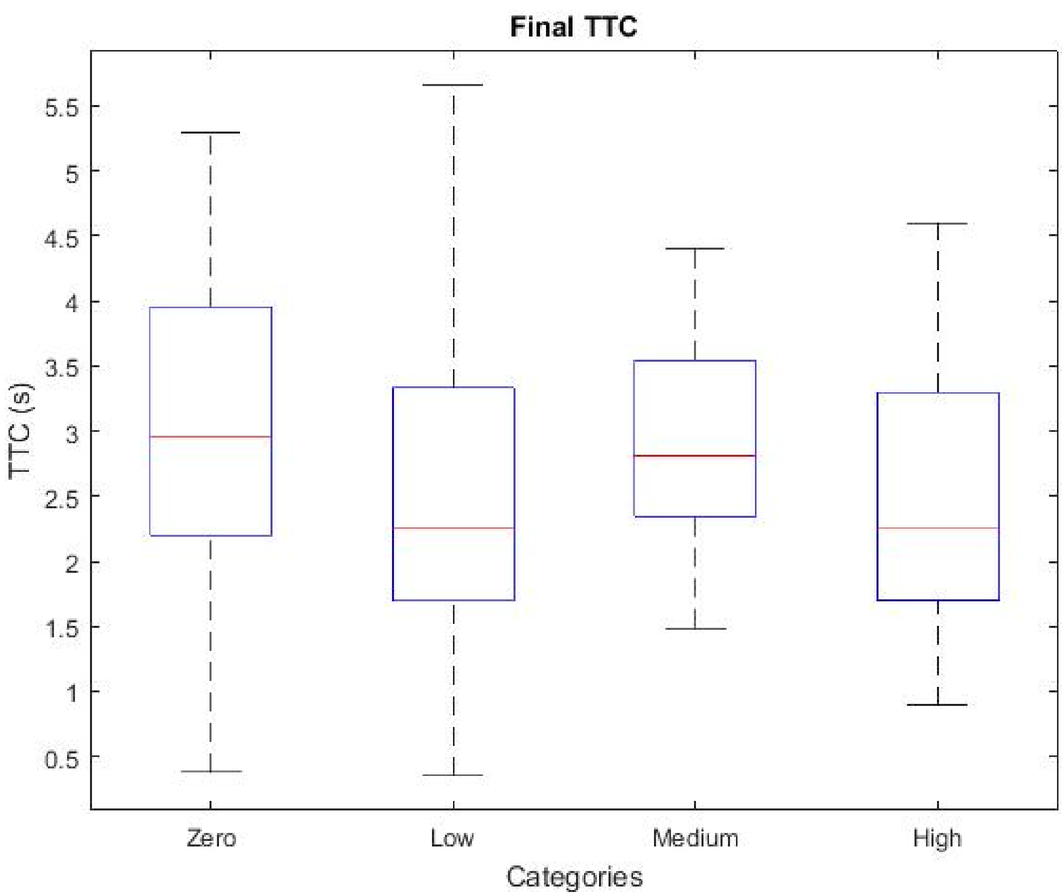


FIGURE 13 Final TTC boxplot.

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 14. There is 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 is not significant, p = 0.5683. Based on these results it is unlikely that the warning system has any effect on the driver's tailway time at the end of the maneuver, but it is possible that some significance may be found with a larger sample.

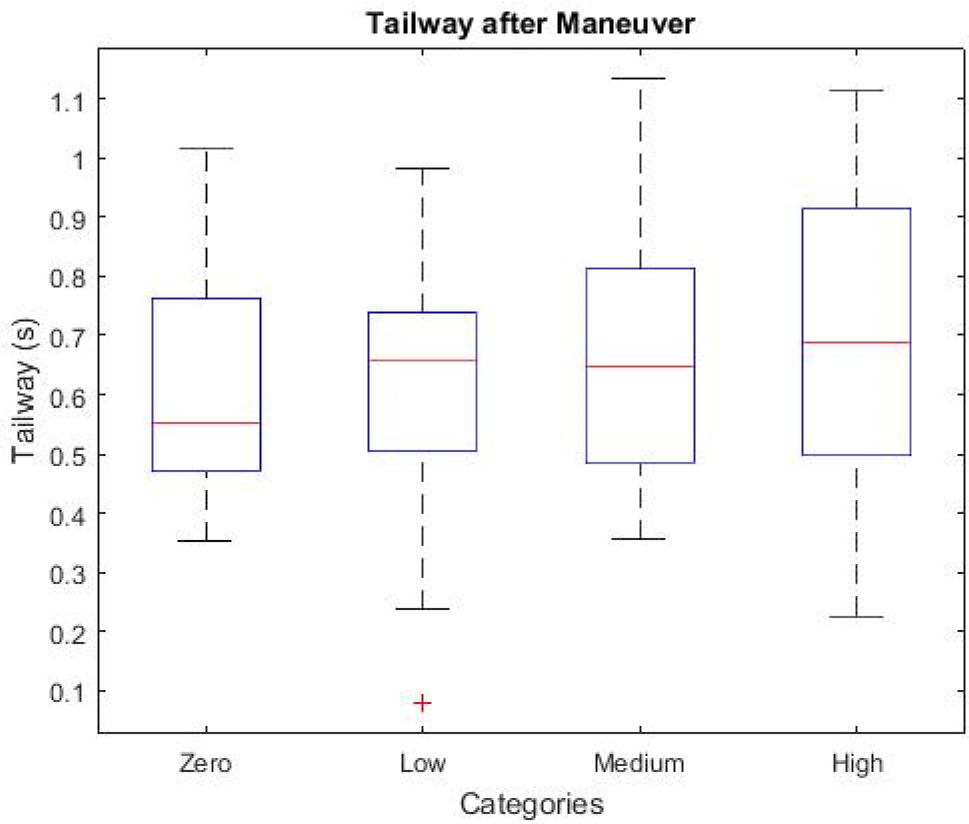


FIGURE 14 Box plot of tailway after the maneuver.

FIGURE 15 illustrates the data collected for the average headways between the simulator and the slow-moving vehicle during the 5s leading up to the onset of the maneuver. This 5s period is analyzed to measure driving behavior during the decision making process. The ANOVA test found significant differences in means of the average headways during the 5s 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 = 0031, and the medium and high MP scenarios, p = 0.0886 as seen in TABLE 9. More specifically the average headway increased as MP increased. This indicates an increase in safety during the decision making process. This is 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 the warning system at such low MP. It is recommended that this question is added to the survey of the future study.

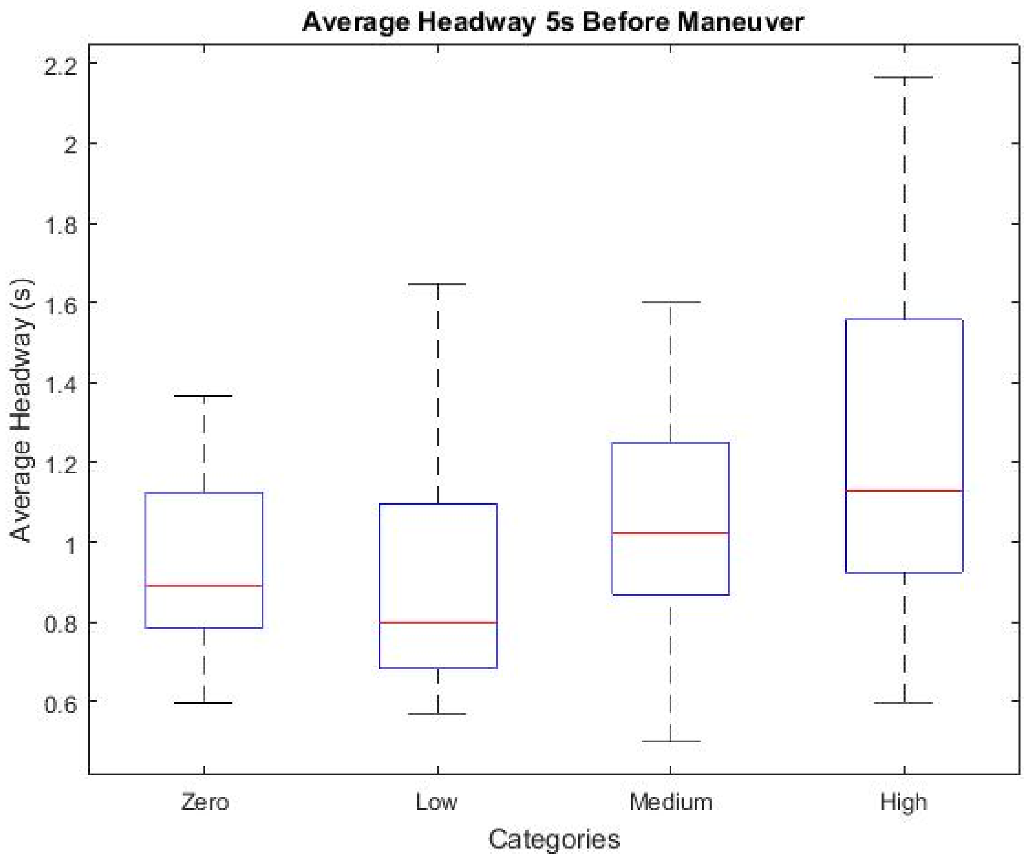


FIGURE 15 Box plot of average headway 5s prior to the maneuver.

TABLE 9 T-test comparisons for average headway 5s before maneuver.

Average Headway 5s 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 16 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, 5s 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 10 further indicates that there are 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 increases at medium and high MP. This increase in headway indicates an increase in safety at the beginning of the maneuver due to the improved awareness of the driver during the decision making process.

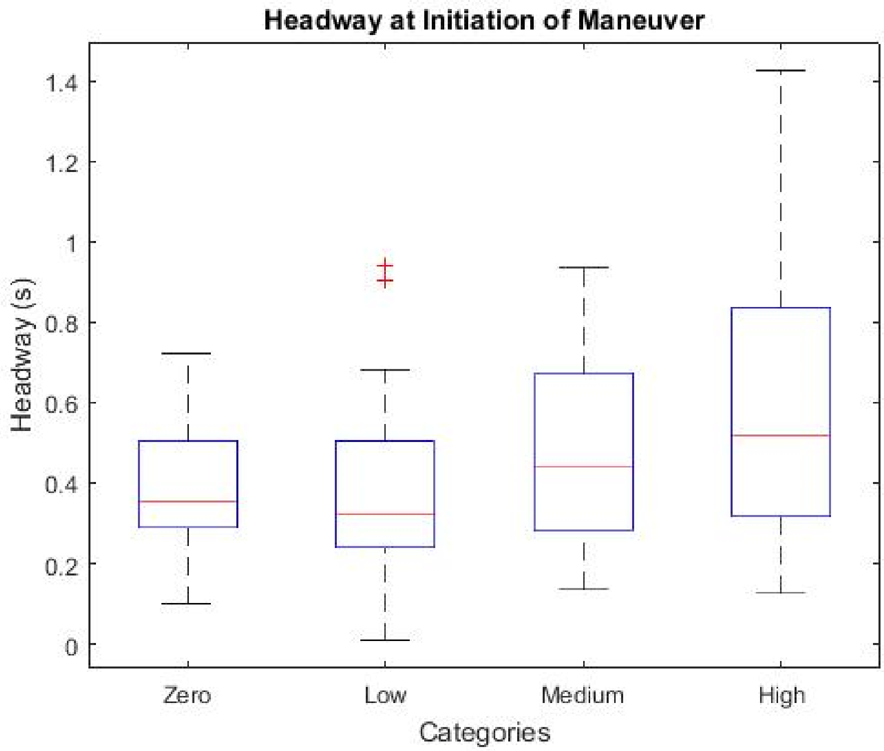


FIGURE 16 Box plot of headway at initiation of maneuver.

TABLE 10 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 17 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 11 indicates that there are 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 = 0148. This parameter is directly impacted by the accepted gap, and the initial headway. Since the accepted gap is similar at each MP, but the headway increases as MP increases it is expected that the time spent in the left lane would increase as the MP increases due to the extended passing zone. While this is 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.

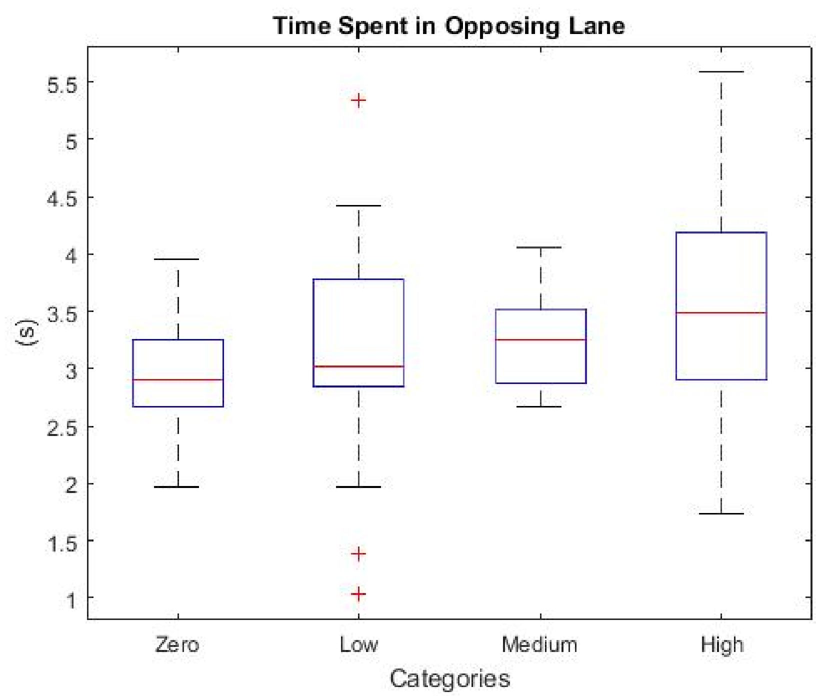


FIGURE 17 Box plots of time spent in opposing lane.

TABLE 11 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

CHAPTER 5. CONCLUSIONS

5.1 Blind Spot Warning Application

The initial study investigated the impact of market penetration levels on the effectiveness of a CV blind spot warning application within a high-fidelity 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 non-parametric tests paired with a post-hoc pairwise test to evaluate the impact of MP on the effectiveness of the blind spot warning application.

The results showed a significant impact of MP on the effectiveness of blind spot warning applications. Although blind spot warning 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 indicate that an MP around 50% is needed to effect a significant impact on this particular type of crash risk. To interpret the results further, it is important to consider the experimental limitations. The experiment was primarily limited by the capabilities of the driving simulator. While the simulator environment did provide a realistic driving experience, it lacked 360 degrees of projection, which prevented the driver from looking over his or her shoulder to observe blind spot vehicles during lane change maneuvers. The experiment also does not account for the potential of existing radar-based blind spot warning systems.

5.2 Do Not Pass Warning Application Pilot Study

This pilot study was conducted to determine the best method for studying the effectiveness of a Do Not Pass Warning (DNPW) system designed under the limitations of CV technology. This warning system was designed to alert drivers of oncoming vehicles on a two-lane two-way rural roadway. The purpose of such an application is to reduce head-to-head collisions during overtaking maneuvers. Using CV technology to provide DNPW messages to the driver is considered ideal because of its ability to collect the speed and location of the opposing vehicle. This information can be used to determine the TTC between the driver and the opposing vehicle and display warning messages when this value reaches an unsafe threshold. Despite the technology's abilities, the use of CV technology has some limitations for such an application. The warnings can only be provided to the driver when the CVs are within the 300m communication range. In addition to this, the warning systems are dependent on the MP of vehicles equipped with CV technology within the network.

This pilot study was conducted 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 were 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 tailway 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 is limited by the abilities of CV technology and does not operate at 100% MP is 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 tailway 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 study, these improvements were only significant at medium and high penetration rates. This increase in headway before the maneuver suggests that drivers were able to remain more conscience of their driving behavior with the assistance of the warning system. This is an indication that this CV application is capable of improving safety during the decision making process at medium and high penetration rates. It is also important to note that the driver spent significantly more time in the opposing lane as MP increased, but this is 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 study was limited and a future study must be conducted with a larger sample size to validate its findings. The results, though, provide insight on the benefits of a DNPW system and indicate that the method performed is an effective method for studying the effectiveness of a DNPW system. To improve the pilot study for the future study, there are a few changes in the scenario to be considered. It is recommended that the limitations of the communication range are further studied by designing multiple scenarios in which the speeds of the ambient traffic vary. This will vary the TTC threshold for the warning system, thus 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 18s and 20s should be added. The survey results also indicate that the warning message may need to be adjusted to be less distracting to drivers at higher MP. An additional survey question should be added as well to measure the participants' trust in the warning system.

5.3 Recommendations

Despite the limitations of this research, the BSW and DNPW studies offer an insight to sensitivity studies for CV safety applications in a simulation environment where human subjects are involved. The studies also provide 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 provides evidence that CV applications will only become an effective means towards improving safety when medium MP rates are met. To further asses 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.

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APPENDIX A: IRB APPROVAL FORM

ACTION ON PROTOCOL CONTINUATION REQUEST

LSU

Institutional Review Board
Dr. Dennis Landin, Chair
130 David Boyd Hall
Baton Rouge, LA 70803
P: 225.578.8692
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TO: Sherif Ishak
Civil Engineering

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: March 16, 2016

RE: IRB# 3505

TITLE: Safety Assessment of Connected Vehicles Technology using a Driving Simulator

New Protocol/Modification/Continuation: Continuation

Review type: Full ___ Expedited X **Review date:** 3/16/2016

Risk Factor: Minimal X Uncertain ______ Greater Than Minimal ______

Approved X **Disapproved** ______

Approval Date: 3/16/2016 **Approval Expiration Date:** 3/15/2017

Re-review frequency: (annual unless otherwise stated)

Number of subjects approved: 100

LSU Proposal Number (if applicable):

Protocol Matches Scope of Work in Grant proposal: (if applicable) ___

By: Dennis Landin, Chairman ______________

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –
Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
6. A prompt report to the IRB of any adverse event affecting a participant potentially arising from the study.
7. Notification of the IRB of a serious compliance failure.
8. **SPECIAL NOTE: Make sure to use bcc when emailing more than one recipient.**

**All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb*

APPENDIX B: IRB CONTINUATION FORM

ACTION ON PROTOCOL CONTINUATION REQUEST

Institutional Review Board
Dr. Dennis Landin, Chair
130 David Boyd Hall
Baton Rouge, LA 70803
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TO: Sherif Ishak
Civil Engineering

FROM: Dennis Landin
Chair, Institutional Review Board

DATE: January 19, 2017

RE: IRB# 3505

TITLE: Safety Assessment of Connected Vehicles Technology using a Driving Simulator

New Protocol/Modification/Continuation: Continuation

Review type: Full ___ Expedited X **Review date:** 1/19/2017

Risk Factor: Minimal X Uncertain ________ Greater Than Minimal ______

Approved X **Disapproved** ________

Approval Date: 1/19/2017 **Approval Expiration Date:** 1/18/2018

Re-review frequency: (annual unless otherwise stated)

Number of subjects approved: 200

LSU Proposal Number (if applicable): 39111 and 42688

Protocol Matches Scope of Work in Grant proposal: (if applicable)

By: Dennis Landin, Chairman ______________

PRINCIPAL INVESTIGATOR: PLEASE READ THE FOLLOWING –
Continuing approval is CONDITIONAL on:

1. Adherence to the approved protocol, familiarity with, and adherence to the ethical standards of the Belmont Report, and LSU's Assurance of Compliance with DHHS regulations for the protection of human subjects*
2. Prior approval of a change in protocol, including revision of the consent documents or an increase in the number of subjects over that approved.
3. Obtaining renewed approval (or submittal of a termination report), prior to the approval expiration date, upon request by the IRB office (irrespective of when the project actually begins); notification of project termination.
4. Retention of documentation of informed consent and study records for at least 3 years after the study ends.
5. Continuing attention to the physical and psychological well-being and informed consent of the individual participants, including notification of new information that might affect consent.
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8. **SPECIAL NOTE: Make sure to use bcc when emailing more than one recipient.**

**All investigators and support staff have access to copies of the Belmont Report, LSU's Assurance with DHHS, DHHS (45 CFR 46) and FDA regulations governing use of human subjects, and other relevant documents in print in this office or on our World Wide Web site at http://www.lsu.edu/irb*

APPENDIX C: BSW PARTICIPANT SURVEY

Participant Survey

BEFORE TESTING

Name: ____

Age: ____

Years with license: _________________________________

Gender: M/F

Does your vision require glasses: YES/NO

If so, Do you have your glasses/contacts: YES/NO (If No, stop here)

Do you suffer from motion sickness: YES/NO

Have you driven a vehicle with Blind spot warnings? YES/NO

Take the Aggressive vs not aggressive driver test now.

AFTER TESTING

Questions:

1. Did you find the visual Blind Spot Warnings Useful? YES/NO
2. Did you find the visual Blind Spot warnings Distracting? YES/NO
3. Did you feel dependent on the visual Blind Spot Warnings? YES/NO
4. Did you feel more comfortable making lane changes with the visual Blind Spot Warning? YES/NO
5. Did you find the auditory Blind Spot Warnings Useful? YES/NO
6. Did you find the auditory Blind Spot warnings Distracting? YES/NO
7. Did you feel dependent on the auditory Blind Spot Warnings? YES/NO
8. Did you feel more comfortable making lane changes with the auditory Blind Spot Warning? YES/NO
9. Would you prefer auditory warnings, visual warnings, both, or neither?
   ____
10. Did you suffer from motion sickness during the simulation? YES/NO
11. Comments:

THANK YOU FOR PARTICIPATING!!!

APPENDIX D: DNPW PARTICIPANT SURVEY

Name: ____________________________________

Age: ___________________________

Gender: M / F

Years with License: ________________

Do you suffer from motion sickness? Y / N

After Test 1:

1. Did you find the visual warnings useful? Y / N

2 Did you find the visual warnings distracting? Y / N

3. Did you feel more comfortable performing the passing maneuvers with the visual warnings?
   Y / N

4. Did you feel dependent on the visual warnings? Y / N

For Instructor:

Market Penetration: _______________

ID: ______________________________

After Test 2:

1. Did you find the visual warnings useful? Y / N

2 Did you find the visual warnings distracting? Y / N

3. Did you feel more comfortable performing the passing maneuvers with the visual warnings?
Y / N

4. Did you feel dependent on the visual warnings? Y / N

Comments:

For Instructor:

Market Penetration: _______________

ID: ______________________________

VITA

Matthew Theriot, a native of Baton Rouge, Louisiana, received his Bachelor's Degree in Civil Engineering from Louisiana State University (LSU) in 2015. He is currently pursuing his Master's Degree in Civil Engineering with a specialization in Transportation Engineering at LSU and anticipates graduating in May 2017. Using his background in Transportation Engineering, Matthew plans to work as a Project Engineer in industry. His goals are to obtain his Professional Engineer license in the upcoming years and eventually become a licensed Professional Traffic Operations Engineer.