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16. Abstract

As a major ITS initiative, the Vehicle Infrastructure Integration (VII) program is to revolutionize transportation by creating an enabling communication infrastructure that will open up a wide range of safety applications. The road-condition warning system is a unique application of VII technology, which is to provide drivers with real-time information about unexpected roadway conditions ahead, such as accidents, speed reduction zones, hazardous weather conditions, etc. The safety effectiveness of the VII-based warning systems needs to be investigated under various driving conditions. In this study, three different types of warning systems: Rural Highway Driver Warning System (RHDWS), Highway Lane Change Warning System (HLCWS) and Work Zone Driver Warning System (WZDWS), were designed and tested in the designed highway scenarios by driving simulator experiments. The experimental results show that all three systems can reduce the crashes in the designed environment. According to the survey result, the system is easy for the driver and helpful to them in driving safely under various driving conditions. The results of this research will be helpful for the decision making on the application of VII technology.

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Vehicle Infrastructure Integration (VII) Based Road-Condition Warning System for Highway Collision Prevention

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ABSTRACT

As a major ITS initiative, the Vehicle Infrastructure Integration (VII) program is to revolutionize transportation by creating an enabling communication infrastructure that will open up a wide range of safety applications. The road-condition warning system is a unique application of VII technology, which is to provide drivers with real-time information about unexpected roadway conditions ahead, such as accidents, speed reduction zones, hazardous weather conditions, etc. The safety effectiveness of the VII-based warning systems needs to be investigated under various driving conditions. In this study, three different types of warning systems: Rural Highway Driver Warning System (RHDWS), Highway Lane Change Warning System (HLCWS) and Work Zone Driver Warning System (WZDWS), were designed and tested in the designed highway scenarios by driving simulator experiments. The experimental results show that all three systems can reduce the crashes in the designed environment. According to the survey result, the system is easy for the driver and helpful to them in driving safely under various driving conditions. The results of this research will be helpful for the decision making on the application of VII technology.

DISCLAIMER

NOTICE

ACKNOWLEDGEMENTS

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EXECUTIVE SUMMARY

The Vehicle Infrastructure Integration (VII) program is to revolutionize transportation by creating an enabling communication infrastructure that will provide a wide range of safety applications. This research is to investigate the application of the VII technology for preventing crash under various driving conditions. For this purpose, three VII-based driver warning systems (RHDWS, HLCWS and WZDWS) were designed and tested in designed testing scenarios by driving simulator experiments.

The Rural Highway Driver Warning System (RHDWS) is designed for preventing run-off-road (ROR) collisions in curvy rural highways. In this system, three types of warnings were provided to the drivers: 1) lane departure warning, 2) curve ahead warning, and 3) speed limit warning. With the help of such systems, drivers would have enough time to adjust their speeds and driving behaviors to respond to the unexpected roadway conditions ahead, such as sharp curves. The experimental results show that this system can significantly reduce the ROR collisions in a rural highway environment. According to the survey of the tested drivers, the system is easy for the driver to use and helpful to them in safely negotiating a curvy rural highway.

The Highway Lane Change Warning System (HLCWS) is designed for preventing the collisions associated with lane changes. The designed system is tested on an urban highway with heavy traffic volume and high speed limits by driving simulator experiments. The test results show that this system will help drivers avoid unsafe lane changes and that the system has the potential to reduce collisions. According to a survey of the tested drivers, the system is easy for drivers to use and helpful in making safe lane changes.

Work Zone Driver Warning System (WZDWS) is designed for preventing the collisions associated with work zones. It includes an in-vehicle driver warning subsystem and a real-time Dynamic Message Sign (DMS) subsystem. To test the effectiveness of the proposed work zone collision prevention system, three different types of driving simulator testing scenarios are generated. The first type is the baseline scenario with the basic traditional work zone safety control measures. The second type is the comparison scenario which uses the prevailing work zone control measures. The third type is the study scenario which employs the proposed VII technology based work zone collision prevention systems. The designed WZDWS system is tested in these three designed scenarios. Qualitative data from survey and quantitative data from driving testing are both collected for assessing the safety benefits of the proposed VII based work zone collision prevention systems. The results of this research indicate that VII technology has the potential to reduce the safety risks at work zones under certain conditions.

TABLE OF CONTENT

LIST OF FIGURES

LIST OF TABLES

CHAPTER 1: INTRODUCTION

1.1 Background

As part of the Intelligent Vehicle Initiative of the United States Department of Transportation (USDOT), the National Highway Traffic Safety Administration (NHTSA) is developing the crash avoidance mitigation concepts for several highway collision types, including Run of Road (ROR), lane change and work zone related collisions. A statistical review of the 2001 General Estimates System (GES) and the Fatality Analysis Reporting System (FARS) databases shows that in 2001, about 40 percent of all in-vehicle fatalities in the United States resulted from ROR crashes *(1, 2),* nearly 69 percent of the ROR crashes occur on rural roads. Lane-change events are closely related to the rear-end crashes, which account for approximately 25% of the total crash population each year *(3).* Over the last five years, the number of persons killed in motor vehicle crashes in work zones has risen from 989 in 2001 to 1,074 in 2005 (an average of 1,068 fatalities a year) *(4).* Besides the severe fatalities, work zone accidents also cause large amounts of property damages, which were estimated to be as high as $6.2 billion per year between 1995 and 1997 with an average cost of $3,687 per crash *(5).*

As a major ITS initiative, Vehicle Infrastructure Integration (VII) technology may provide new opportunities for preventing the three different types of collisions mentioned above. The Vehicle Infrastructure Integration (VII) program is to create an "enabling communication infrastructure", which means that real-time traffic roadway information can be exchanged between the roadside and vehicles. It uses a widely deployed communication system known as "dedicated short-range communications" (DSRC). DSRC equipment operating in the 5.9 gigahertz frequency range is placed on the roadways and within the vehicle (US DOT 2007). With its ability to enable information exchange between vehicles and road side infrastructures, VII technology is expected to increase driver's awareness of the dangerous traffic and road conditions ahead, such as sharp curves, work zones, lane closures and bad weather, thus reducing the risks of accidents. Currently, this application is still in the conceptual development stage.

1.2 Research Objectives

The goal of this research is to investigate the application of the VII technology in preventing run-off-road collision on rural highways, collisions associated with lane changes maneuver and work zones by using an advanced driving warning system and to estimate the safety benefits of the proposed warning system. To achieve these objectives, the research will:

1) Design three different types of VII-technology based driver warning system:
    a. Rural Highway Driver Warning System(RHDWS),
    b. Highway Lane Change Warning System(HLCWS), and
    c. Work Zone Driver Warning System(WZDWS)
2) Test the designed system by conducting driving simulator experiments.

To achieve the above research objectives, different driving scenarios are designed for the three different types of warning systems and programmed in the driving simulator environment.

For the RHDWS, two driving scenarios were designed: (1) the baseline scenario (normal situation: driving a vehicle on a two-lane, rural highway without any warning system, and (2) the study scenario: driving a vehicle with designed warning system on the same rural highway.

For the HLCWS, also two driving scenarios were created in the simulation experiments: (1) the baseline scenario: driving a vehicle without any warning system on a three-lane urban highway and (2) the study scenario: driving a vehicle with an on-board HLCWS on the same urban highway.

For the WZDWS, three different types of driving scenarios were designed and tested: (1) the baseline scenario with the basic traditional work zone safety control measures. (2) the comparison scenario which uses the prevailing work zone control measures, and (3) the study scenario which employs the proposed VII technology based work zone collision prevention systems.

After creating these driving scenarios in a driving simulator environment, the test subjects were recruited and participated in the driving simulator experiments. Then, the effectiveness/safety benefits of the proposed VII technology based driver warning system under various scenarios were evaluated.

1.3 Organization of the Chapters

This report is organized in the following order. Chapter 2 reviews the VII concept and the existing studies on preventing the three different types of highway collisions, i.e. run off road (ROR), lane change and work zone related collisions. Chapter 3 introduces the design of the VII based driver warning systems, i.e. RHDWS, HLCWS, and WZDWS. Chapter 4 describes the methodologies for evaluating the performance of the proposed driver warning systems. Chapter 5 presents the evaluation results of these three driver warning systems. Finally, Chapter 5 gives the conclusion, recommendation, and future direction of this research.

CHAPTER 2: LITERATURE REVIEW

In this chapter, literatures in two aspects are reviewed: 1) VII technology and its potential applications, and 2) existing studies on preventing the three different types of highway collisions, i.e. ROR, lane change and work zone related collisions.

2.1 VII Technology and Its Potential Applications

Vehicle Infrastructure Integration (VII) combines leading edge technologies – advanced wireless communications, on-board computer processing, advanced vehicle-sensors, GPS navigation, smart infrastructure and others – to provide the capability of two way communication between the vehicles and the central controllers. Because of this communication capability, vehicles are able to identify threats and hazards on the roadway and communicate this information over wireless networks to give drivers alerts and warnings. Figure 1 gives the system architecture of VII technology.

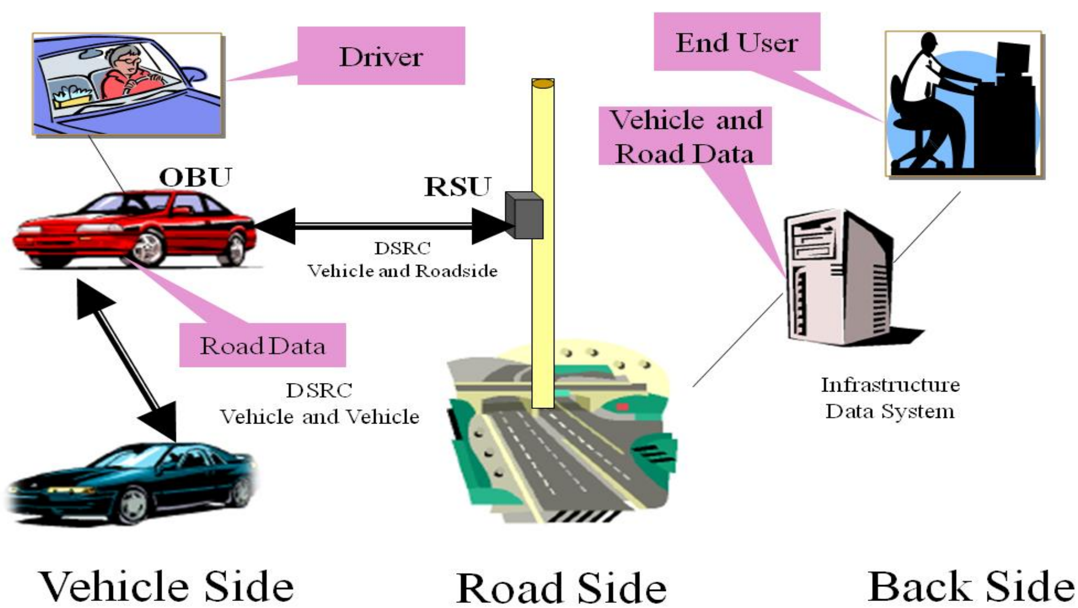


Figure 1 System Architecture of VII Technology
(Source: US DOT, 2003).

The most critical communication technology that forms the backbone of the whole VII technology architecture is the Dedicated Short Range Communication (DSRC) system that enables the data transmission between the vehicles themselves' Onboard Unit (OBU) and the Road Side Unit (RSU) in order to provide secure, reliable communication links between vehicles and the infrastructure. OBU is a DSRC transceiver. RSU is an interface to the backbone networks with enough storage capacity. Often, RSU receives traffic probe data records from the OBU via DSRC radio link. Then, it stores, aggregates and forwards the probe records to the backbone networks. This technology utilizes the 5.9 GHz frequency as the wireless channel which permits a much higher data transmission rate than the lower-frequency 915 MHz band (the commonly used frequency band for civilian purposes). It provides 75 megahertz of spectrum for DSRC applications. The 915 MHz frequency has only 12 megahertz of spectrum available which is shared with cordless telephones, garage door openers, and many other non-licensed wireless applications. While for the frequency band of 5.9 GHz, other users in the band include only military radars and satellite communications systems *(6).* With the powerful VII technology, a lot of applications have been proposed including the Intersection Collision Avoidance System. Figure 2 illustrates how this system works.

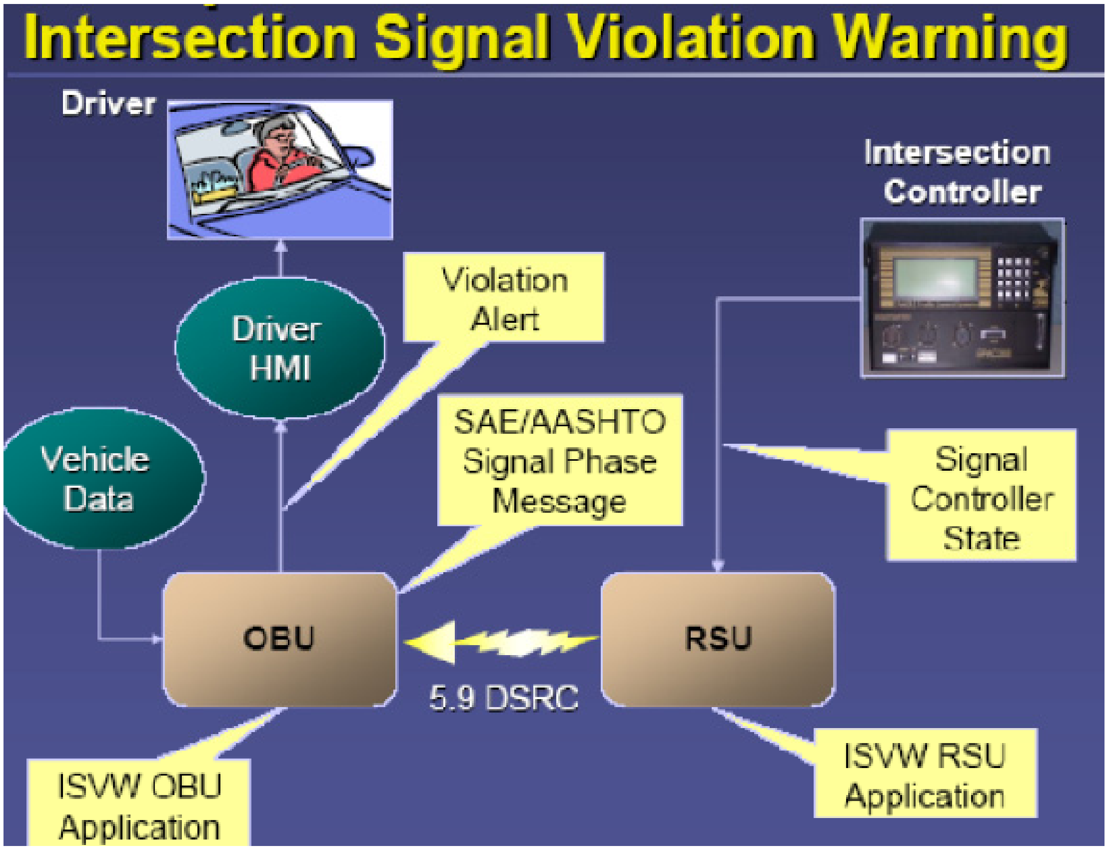


Figure 2 System Configuration of Intersection Collision Avoidance System
(Source: US DOT 2003)

In this Intersection Collision Avoidance System, the RSU will be able to receive data from the approaching vehicles about their speed, acceleration and direction. Based on these data and the data from the intersection devices, the processor will calculate the collected data to identify if the movements of the vehicles are safe. Whenever a potential danger is detected, the RSEs will communicate the RSU in vehicle via the DSRC system to give warning to the driver *(7)*. Another VII application is to enhance the safety of public transit systems. It includes three sub-functions: signal violation warning, stop sign violation warning and curve speed warning. The first two sub-functions use communication between roadside units and vehicles to warn drivers that they are at risk of violating a red light or stop sign. The third sub-function will make a calculation based on vehicle dynamics and provide a warning, transmitted from the roadside unit to the vehicle, when the driver's speed is calculated to be too fast for an upcoming curve *(8)*.

2.2 Existing Studies on Preventing the Three Different Types of Highway Collisions

2.2.1 Existing studies on ROR collision prevention on rural highway

Geographic and economic constraints require unusual geometry configurations, such as curves and slopes, on some sections of the rural highway system. Currently, static message signs are used for providing the information to drivers. However, due to the high speeds on rural highways and drivers' inattention to the static signs, a high occurrence of ROR collisions exists.

Numerous studies have been conducted on deploying different types of technologies for the prevention of ROR crashes. For example, in 2007, as a part of the Integrated Vehicle-Based Safety Systems (IVBSS) initiative of the ITS program, the Volpe National Transportation Systems Center (Volpe Center) conducted an independent evaluation of integrated safety systems for motor vehicles in support of the National Highway Traffic Safety Administration (NHTSA) *(9)*. In this study, on- road tests were performed using a 2007 Honda Accord vehicle equipped with a curve speed warning (CSW), lane departure warning (LDW) and other prototype warning systems. The vehicle was then driven in an uncontrolled driving environment on public roads. The results of this study indicated that the prototype warning system showed improved and consistent performance during the on-road verification test series.

A study by LeBlanc et al *(10),* summarized the results from the Intelligent Vehicle Initiative (IVI) Road Departure Crash Warning System Field Operational Test (RDCW FOT) project. This project developed, validated, and field-tested a set of technologies that provide warnings to drivers when their vehicles are drifting from the lane, and when they are approaching a curve too fast to safely negotiate the curve. The field test used 11 passenger sedans equipped with a RDCW system and a data acquisition system that compiled a massive set of numerical, video, and audio data. Seventy-eight drivers each drove a test vehicle, unsupervised, for four weeks. The test results showed that, with the assistance of RDCW system, drivers showed improvement in keeping in lane by remaining closer to the lane center and reducing the number of excursions near or beyond the lane edges.

In 2005, Monsere et al *(11)* evaluated a roadside Advanced Curve Warning System (ACWS) at one study site on Interstate Highway 5 in Oregon. This roadside ACWS had the following key elements: a dynamic message sign (DMS), a speed measurement device (a radar unit), a controller unit, and computer software to control the DMS. Three measures of effectiveness were used in the evaluation of the system: 1) speed changes for passenger cars and commercial vehicles; 2) the speed distribution difference for passenger cars and commercial vehicles; and 3) public response to the sign. The evaluation results indicated that this roadside ACWS was effective in reducing the mean speeds of passenger cars and commercial vehicles. Surveys of motorists at nearby rest areas revealed a positive perception of the ACWS.

In McMillan et al *(12),* collision countermeasure systems (CMS) were established to prevent ROR crashes. The system determined the vehicle heading using a video camera and calculated a measure for safety assessment, i.e., Time-to-Line Crossing (TLC). The TLC predicted the time until a front would cross the edge of the lane. A three-stage simulation study was conducted to evaluate the effects of road curvature, pavement friction, shoulder rolling resistance, vehicle speed, and other factors on the performance of the system. The results of this study showed that the CMS is effective for reducing the number of ROR crashes.

2.2.2 Existing studies on preventing the crashes related to highway lane change

Different types of Lane Change Warning (LCW) systems have been designed and developed by previous studies. In 2000, the Space and Electronics Group of TRW developed a collision avoidance system consisting of two warning subsystems *(13).* The first subsystem detects vehicles in a defined proximity zone to the side of the subject driver's vehicle, including the region referred to as the "blind spot". The second subsystem detects vehicles that are farther behind the subject driver's vehicle than the proximity zone and that are approaching the proximity zone at high rates of speed. For both subsystems, warnings are given by flashing a red triangle in the rear view or side view mirrors. The developed systems were evaluated by driving simulator experiments and by surveying the tested drivers. The test results show that these systems do help drivers in the process of changing lanes be aware that other vehicles are nearby and located in their blind spots.

Similar research was conducted by Svenson et al. in 2005*(14).* In this study, five types of lane change collision avoidance systems were designed and tested by using driving simulator experiments and surveying the tested drivers. It was found the level of acceptance of the systems varied between drivers, depending on their ages and the extent of their driving experience. Ruder et al. *(15)* proposed a highway lane change assistance system that could monitor the areas behind and beside the subject vehicle using vision and radar sensors. If a dangerous object were detected in the destination lane, a warning was displayed as a red signal near the exterior mirror. This assistance system was calibrated on real world highways, but the performance of the system has not been evaluated by any quantitative criteria.

In a U.S. Department of Transportation (U.S. DOT) sponsored Integrated Vehicle-Based Safety Systems (IVBSS) program, a multi-radar sensors based LCW system has been designed. In this system, four short-range radars and two side-looking cameras are distributed along the sides of the vehicle, which can help detect the ambient vehicles on the neighboring lanes. The frequency of the radar sensors used for the light duty vehicle is 24GHZ and it can detect the vehicles within 15 meters. For the heavy duty vehicle, the frequency of the radar sensor is 5.8 GHZ and its maximum detection is 10 meters *(16).*

In addition, some vehicle manufactures have developed their LCW systems mainly based on two types of technologies: 1) the video camera based sensors and 2) the radar based sensors. These LCW systems are now available in certain models of vehicles. Volvo uses video cameras for its Blind Spot Information System *(17).* Each camera, embedded in the side-view mirrors, monitors an area about 33 feet behind and about 10 feet to each side. The system is available for all of Volvo's cars. The following LCW systems use multi-radar sensors to detect the vehicles on the destination lanes: Audi's Side Assist system, General Motors' Side Blind Zone Alert system, LCW system for the new BMW 7 Series and Valeo Raytheon's Lane Change Assistance System *(17, 18, 19)*. Both types of sensor-based LCW systems have some limitations. For the video camera-based LCW system, because the camera image is sensitive to illumination conditions and weather conditions, the detection is not accurate at night or on rainy days. Also, the video camera is easily obscured by dust and dirt. Most importantly, when the vehicle is moving with high speed, the video based sensors cannot detect the location and speed of the ambient vehicles very accurately. For the radar-based LCW systems, the major limitation is that the detecting distance is limited. For example, for the LCW system developed by IVBSS program, the maximum detection distance is 15 meters, which is not enough to provide a sufficient warning in some circumstances *(16).*

2.2.3 Existing studies on work zone crash prevention

Since the work zone safety problem has been a concern for decades, a lot of different measures have been proposed to improve the safety at work zones. Traditional work zone traffic control measures include static work zone speed limit signs, flashing arrow signs and police enforcement *(20).* These work zone traffic control measures have been used for decades and have proven to be effective in reducing accidents at work zones. However, due to the dramatic increase of work zone activities in our highway systems, the number of crashes and fatalities are still unacceptable. Various efforts have been conducted to find new ways to improve safety at work zones. Much of the effort has been focusing on utilizing the recently developed Intelligent Transportation System (ITS) technologies. The transportation agencies of Maryland, Iowa, Kentucky, Nebraska, Illinois and Ohio have used ITS technologies to operate Smart Work Zones *(21, 22, 23, 24).* In these "Smart Work Zones", speed sensors are placed at several sites within the work zone to determine the traffic conditions at these locations. Then, speed data are transmitted to a portable, central control system located at the worksite that processes the incoming data. The speed data are analyzed to determine if a speed-advisory, delay-advisory, or route-diversion message should be displayed. If the data indicate that some type of message should be displayed, the central control system will transmit a signal to a Changeable Message Sign (CMS), Highway Advisory Radio (HAR), or other device to alert drivers. However, even though manufacturers are promoting this kind of technology, test results are not beneficial for all test sites *(24).* Tudor et al. *(25)* gave a more detailed study to introduce the system design, implementation and test results of a smart work zone in Arkansas called Automated Data Acquisition and Processing of Traffic Information in Real Time (ADAPTIR). The system layout of ADAPTIR is shown in Figure 3.

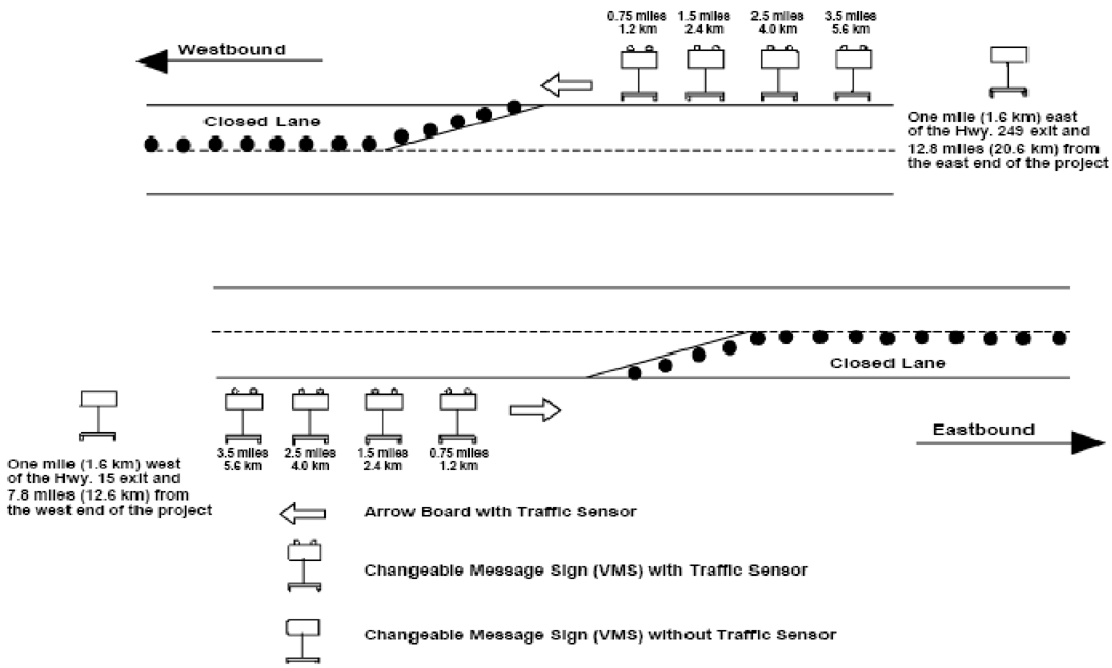


Figure 3 ADAPTIR System Layout, Lonoke County Site, Arkansas
(Source: Tudor et al., 2003)

This system primarily consists of three components, the central system controller, two Highway Advisory Radios (HARs) and five Changeable Message Signs (CMSs). The speed sensors attached on the CMSs will transmit the information to the central system controller and then the controller will give instructions to both the HARs and the CMSs. These systems worked out well for the testing site, reducing both the fatal and rear-end crashes.

A Variable Speed Limit (VSL) system has been introduced by *Kang et al., 2004 (26).* This system includes speed sensors, variable speed limit signs, variable message signs and a central processing unit. The configuration of this system is shown in Figure 4.

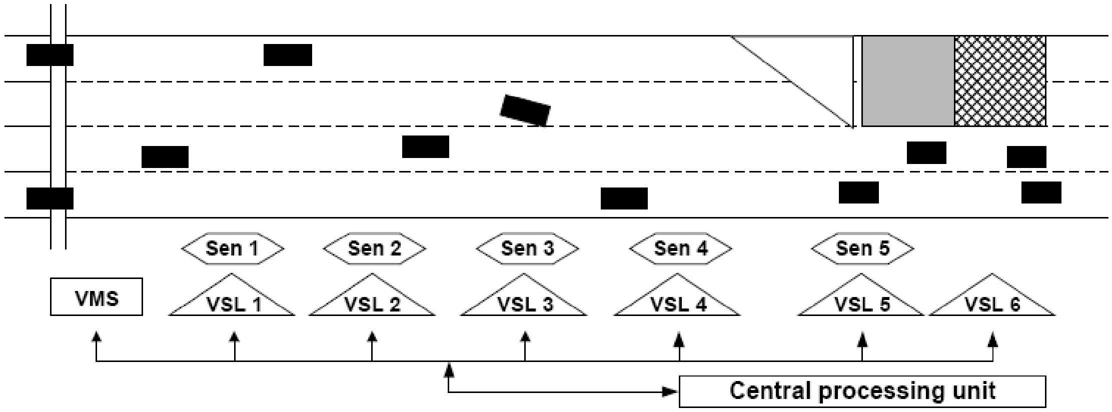


Figure 4 Configuration of VSL System.
(Source: Kang et al., 2004)

In this system, the central processing unit will calculate the optimal speed limit for each of the VSLs based on the speed information collected by the speed sensors and then give instructions to these VSL signs to display the optimal speed limit along the work zone site.

CHAPTER 3: DESIGN OF VII BASED DRIVER WARNING SYSTEMS

This chapter is to present the concept design of the proposed three VII technology based driver warning systems, i.e. Rural Highway Driver Warning System (RHDWS), Highway Lane Change Warning System (HLCWS), and Work Zone Driver Warning System (WZDWS).

3.1 Design of VII based Rural Highway Driver Warning System

According to the VII technologies, the driver warning system was designed with three types of warning functions: 1) speed limit warning, i.e., a warning is given if the speed of the vehicle exceeded the posted speed limit; 2) curve ahead warning, i.e., a warning is given if there was a curve 45 meters ahead; and 3) lane departure warning, i.e., a warning is given if a substantial deviation from the center line of the lane were detected. Figure 5 demonstrates the basic principles of these three warnings functions. With the speed limit warning function, when a vehicle is being driven on the roadway, the OBU in this vehicle monitors its speed and sends this information to the RSU. At the same time, the RSU sends the speed limit information back to the OBU. If the vehicle's speed exceeded the posted speed limit, an audible warning, "watch your speed, speed limit is XXX," is given to the driver. With the curve ahead warning function, when the vehicle is moving towards a sharp curve, the RSU sends the curve information and the correspondent speed limit information for the curve to the OBU; then, an audible warning, "Right/Left Curve Ahead, Speed Limit is XXX", is given to the driver. With the lane departure warning function, the exact location of the vehicle in the lane are determined according to its distance from two RSUs, i.e., R_1 and R_2, as shown in Figure 5. Then, if the deviation of the vehicle is greater than a given deviation distance (DD) threshold, an audible warning, "Keep in the center of the lane," will be given to the driver.

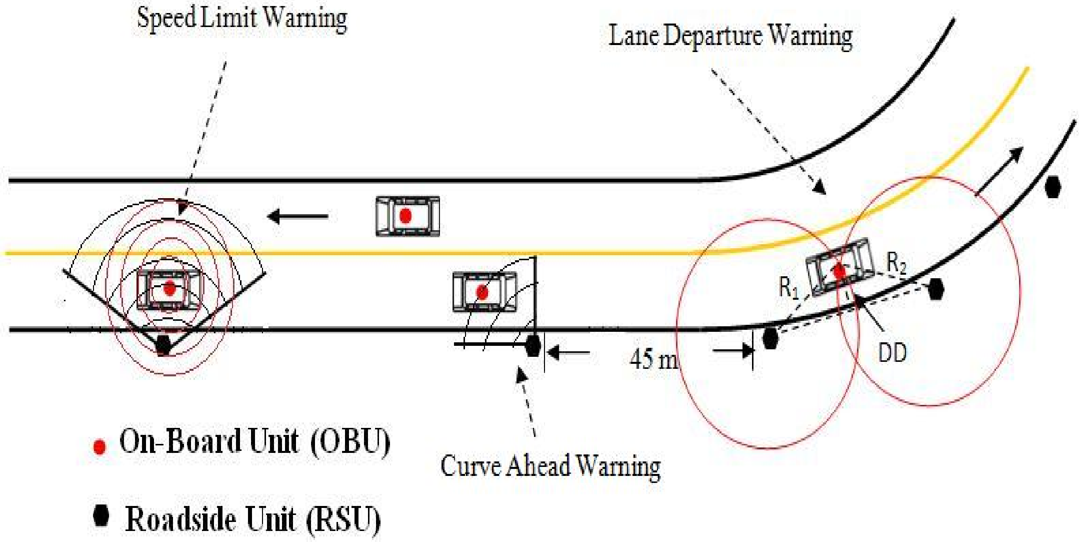


Figure 5 Three Warning Functions for the VII Technology Based Rural Highway Driver Warning System

As shown in Figure 6, the deviation distance *(DD*) is the distance between the center of the vehicle and the centerline of the lane. Based on the *DD*, the following two events can be defined: 1) if the *DD* of the vehicle is greater than half of its width (0.778 meter for the testing vehicle used in this study), a critical event occurs and 2) if the *DD* of the vehicle is greater than 1.20 meters (where the test vehicle is already across the edge the road), an ROR event occurs. The definitions of these two events are presented in Figure 6. If either of these events is detected (i.e., *DD* > *0.778 meter*), the lane departure warning will be provided to the driver.

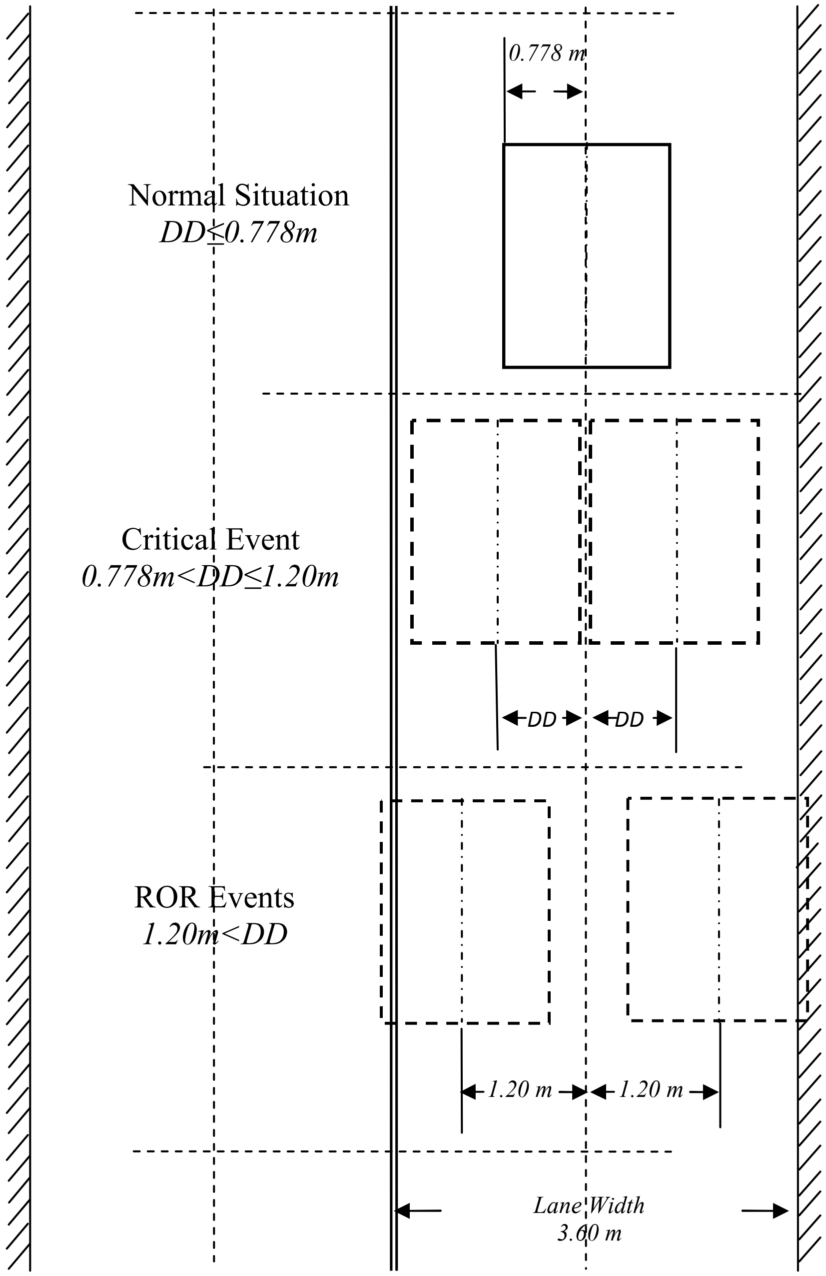


Figure 6 Events Defined Based on Deviation Distance (DD)

3.2 Design of VII based Highway Lane Change Warning System

A VII technology based Highway Lane Change Warning System (HLCWS) has been designed according to the diagram presented in Figure 7. After the driver gives the lane change signal, the on board unit (OBU) on the subject vehicle will communicate with the OBUs on the nearby vehicles through a dedicated short-range communication (DSRC) device to obtain information about the nearby vehicles in the destination lane, such as their velocities, and rates of acceleration. At the same time, the Road Side Unit (RSU) will also communicate with the OBU through DSRC to provide the vehicles positions and the pavement surface friction information detected by the road side sensors. Then, the nearby vehicles that are in the destination lane and closest to the subject vehicle can be identified, and the potential risk of the subject vehicle's colliding with these vehicles can be assessed according to a designed warning strategy. Finally, based on the results of the collision risk assessment, a warning will be given to the driver of the subject vehicle through a human machine interface (HMI) (e.g., an audible warning interface as used in this study) indicating that it is not safe to make the lane change. Note that, the OBU can also be equipped with some radars sensors to collect information about the relative positions, speeds and acceleration rates of the ambient vehicles that are not installed with VII systems.

Compared with the previously designed LCW systems, the VII based HLCWS is recommended for the following reasons. First, DSRC technology is capable of high wireless data exchange rate and large transmission range *(27).* The normal size message can be delivered less than 100 milliseconds and transmission range can extend to almost 1,000m. Therefore, compared with radar and camera based LCW systems, the VII based HLCWS has much longer detection distance. Thus, even the ambient vehicles are far from the subject vehicle, it still can be detected by the subject vehicle immediately. Second, the VII based HLCWS can provide more accurate and real time roadway condition information from the RSUs, such as the pavement surface friction in different weather conditions. It will allow the HLCWS to assess the lane change risk more accurately.

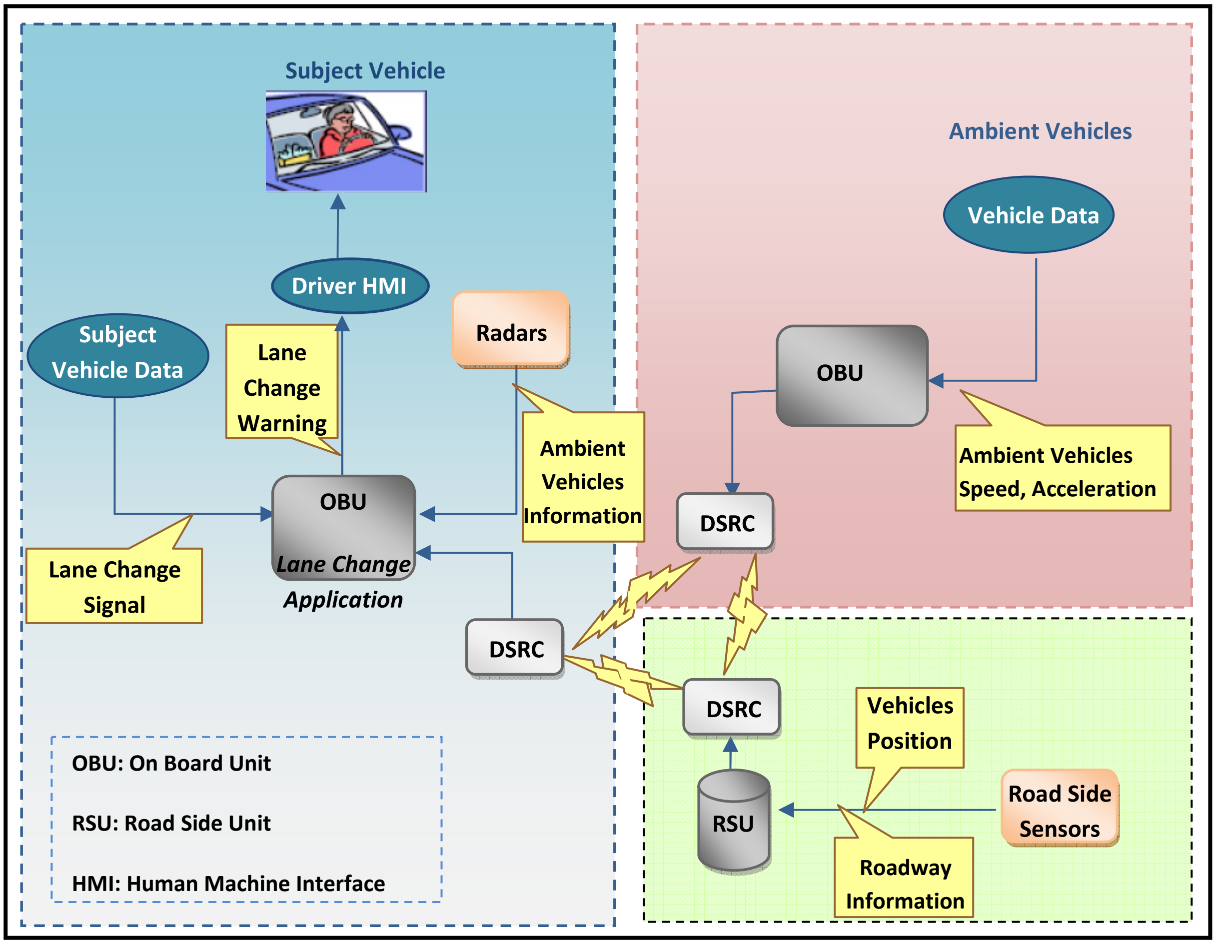


Figure 7 Diagram of VII based Highway Lane Change Warning System

When the subject vehicle has completed the lane change and is in the destination lane, two dangerous situations may occur, as shown in Figure 8: (a) there may be a vehicle (vehicle F) behind the subject vehicle in the destination lane, and vehicle F may be moving at a faster speed than subject vehicle S. In this case, vehicle F is forced to decelerate in order to avoid a collision with the subject vehicle and (b) there may be a vehicle (vehicle L) ahead of the subject vehicle that is traveling at a slower speed than the subject vehicle. In this case, the subject vehicle S is forced to decelerate in order to avoid a collision with vehicle L. In both situations, if the initial distance between the subject vehicle S and the vehicle in the destination lane (either vehicle F or vehicle L) is not large enough, after the lane change, the driver of the vehicle in the following position (vehicle F or vehicle S) will not be able to avoid a collision. Therefore, the warning system is designed to warn the subject driver that the subject vehicle's distance from the nearby vehicles is not sufficient for a safe lane change. Following is the detail description of the development of the warning strategies for both situations.

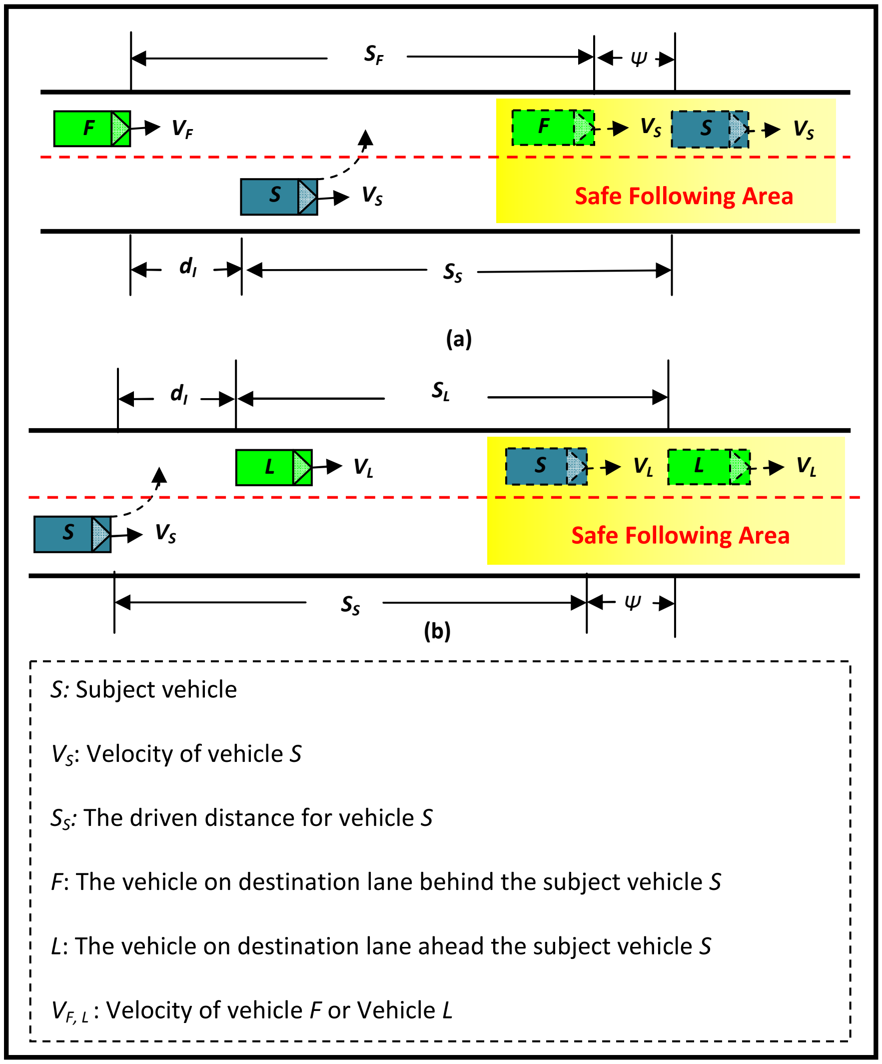


Figure 8 Schematic View of a Lane Change Maneuver

In Situation 1, shown in Figure 8 (a), the subject vehicle S changes to the destination lane with velocity VS. The following vehicle F in the destination lane has a higher velocity VF (VF > VS), and the driver must decelerate until its speed is less than or equal to the speed of the subject vehicle S. Then, they are in a safe following condition (VF ≤ VS). The highlighted area in Figure 8 (a) indicates the start of the safe following condition. Assuming that vehicle F has a constant deceleration, the time needed for vehicle F to decelerate to the same speed as the subject vehicle S can be calculated as:

$$t_{brake} = \frac{V_S - V_F}{a_{\max}} \quad (1)$$

V_S: velocity of subject vehicle

V_F: velocity of vehicle F

a_{max}: deceleration rate for vehicle F

The driving distance for vehicle F and vehicle S before they reach the safe following condition can be calculated as:

$$S_F = V_F(t_{brake} + t_{reaction}) + \frac{1}{2} a_{\max} t_{brake}^2 \quad (2)$$

$$S_S = V_S(t_{brake} + t_{reaction}) \quad (3)$$

$t_{reaction}$ is the reaction time for the following vehicle F to response to the dangerous situation after the lane change.

In order to prevent a collision between the subject vehicle and the following vehicle F, the initial distance between these two vehicles should be large enough to allow the subject vehicle S and the following vehicle F to keep a safe distance before they reach the safe following area (the highlighted area in Figure 8(a)). In other words, the driving distance of the subject vehicle S (S_S) plus the initial distance between the two vehicles (d_I) should be greater than the driving distance of following vehicle F (S_F) and a buffer distance (Ψ), which can be expressed mathematically by the following inequality:

$$d_I + S_S > S_F + \Psi \quad (4)$$

Inequality (4) is identical to

$$d_I > S_F + \Psi - S_S \quad (5)$$

In Situation 2 shown in Figure 8 (b), the subject vehicle S changes to the destination lane with velocity V_S. The vehicle L in front of the subject vehicle on the destination lane has a lower velocity V_L than the subject vehicle ($V_L < V_S$). Therefore, the subject vehicle S is forced to decelerate until its speed is less than or equal to the speed of vehicle L. Then, they are in the safe following condition ($V_S \leq V_L$). The highlighted area in Figure 8(b) indicates the start of safe following condition. Assuming that the subject vehicle has a constant deceleration, the time needed for the subject vehicle to decelerate to the same speed as vehicle L can also be calculated as:

$$t_{brake} = \frac{V_L - V_S}{a_{\max}} \tag{6}$$

V_S: velocity of subject vehicle S

V_L: velocity of vehicle L

a_{max}: deceleration for vehicle S

The driving distance for vehicle L and vehicle S before they reach the safe following condition can be calculated as:

$$S_S = V_S(t_{brake} + t_{reaction}) + \frac{1}{2} a_{\max} t_{brake}^2 \tag{7}$$

$$S_L = V_L(t_{brake} + t_{reaction}) \tag{8}$$

$t_{reaction}$ is the reaction time for the driver of subject vehicle S to respond to the dangerous situation after the lane change.

Similar to Situation 1, in order to prevent a collision between the subject vehicle and the vehicle ahead (vehicle L), the initial distance between these two vehicles should be large enough to allow these two vehicles to keep a safe distance before they reach the safe following area (the highlighted area in Figure 8(b)). In other words, the driving distance of vehicle L (S_L) plus the initial distance between the two vehicles (d_I) should be greater than the driving distance of the subject vehicle S (S_S) and a buffer distance (Ψ), which can be expressed mathematically by the following inequality:

$$d_I + S_L > S_S + \Psi \tag{9}$$

Inequality (9) is identical to

$$d_I > S_S + \Psi - S_L \tag{10}$$

Therefore, when the driver of the subject vehicle signals a lane change, the warning system will first determine whether situation one or situation two exists, based on the speed and location information collected through the DSRC devices in OBUs of the subject and nearby vehicles. If situation one exists, Inequality (5) will be used to determine whether the initial distance (d_I) is long enough for a safe lane change; if situation two exists, Inequality (10) will be used for the same purpose. In both situations, an audible warning, "It is not safe to change lanes", will be given to the driver if it is found that the initial distance (d_I) is not long enough for making the lane change safely. In all other conditions, it is safe to make lane changes, and no warnings will be given.

In this study, the values of parameters used in Equations (1) to (10), which are listed in Table 1, are based on a previous study conducted by Ruder et al. in 2002 *(15).* Note that, in this table, the value of the maximum deceleration rate only reflects the dry pavement surface condition. On the rainy day or snowy day, the value of the maximal deceleration rate will be different due to the different roadway surface friction conditions. Thus, by using the VII based technology, the proposed HLCWS can use different maximum deceleration rates for different weather conditions to increase the accuracy of the warning because the real time pavement surface friction information can be obtained from the road side sensors.

Table 1 Value of Relevant Parameters

Parameter	Value
Reaction Time	$t_{reaction} = 1.0\ s$
Deceleration	$a_{max} = -2.5 m/s^2$
Breaking Time	$t_{brake} = 2.0\ s$
Buffer Distance	$\Psi = 20\ feet$

3.3 Design of VII based Work Zone Driver Warning System

AVII based work zone collision prevention system is proposed for prevent the work zone related collisions. Figure 9 shows the conceptual design of the proposed VII based work zone warning system.

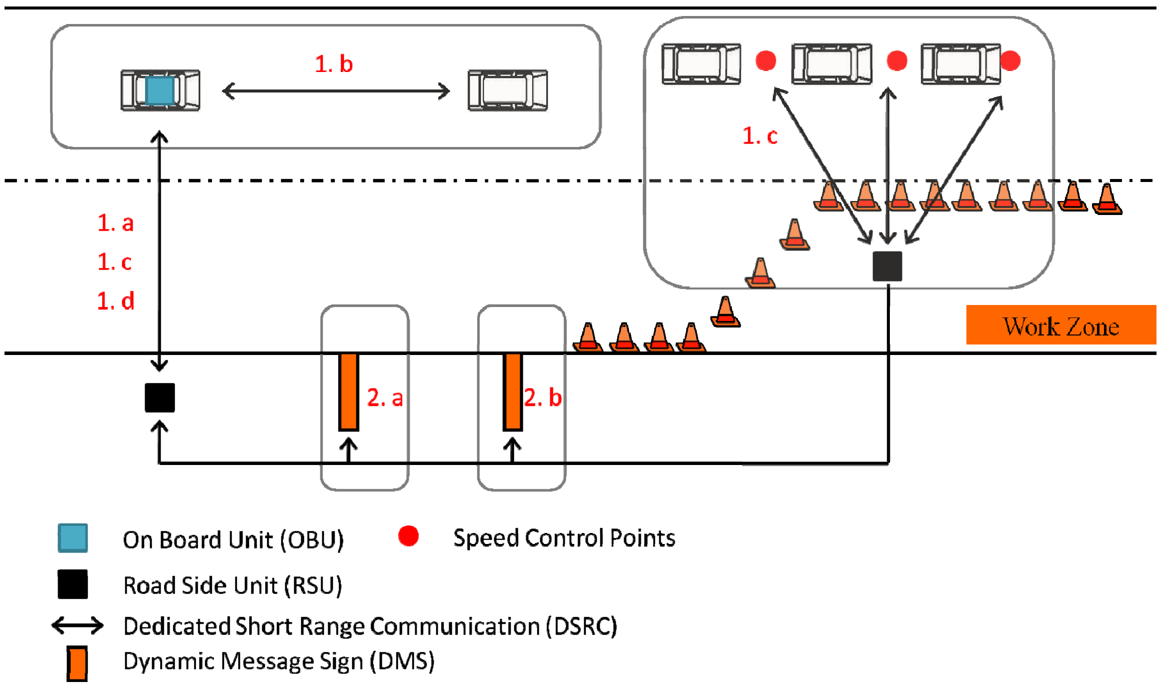


Figure 9 Proposed VII based Work Zone Driver Warning System

The proposed VII based work zone collision prevention system includes the following two sub-systems:

1. In-Vehicle Driver Warning System

Generally speaking, the in-vehicle driver warning system utilizes the Dedicated Short Range Communication System (DSRC) to transfer data between OBUs and RSUs. The system will then give voice warnings to the drivers based on different potentially dangerous situations. It provides the following four types of warnings. The communication flow of these four types of warning is highlighted in Figure 9 as 1.a, 1.b, 1.c and 1.d.

a. Work Zone Presence Warning

This warning strategy is shown as "1.a" in Figure 9. When a vehicle moves into the communicate range (up to 300 ft) of the RSU, the RSU will send the information of the "work zone ahead" to the OBU on the vehicle. The vehicle will then give out a voice message to remind the driver of the upcoming work zone and the geometric layout of the work zone, whether it is one lane closed or one side closed.

b. Headway Warning

This warning strategy is shown as "1.b" in Figure 9. The OBUs on adjacent vehicles will constantly update their position and speed then send the information to each other. Note that, if the vehicle in front of it does not have VII system installed, the sensors installed in the roadway will collect the vehicle location information and send it to the subject vehicle through RSUs. With this information, the vehicle will be able to calculate the headway between itself and the vehicle in front of it. If, the calculated headway is smaller than a certain threshold, (three seconds in this study), a voice warning message will be given to the driver which reminds the driver to keep a safe headway.

c. Work Zone Prevailing Speed Warning

This warning strategy is shown as “1.c” in Figure 9. The OBUs of all the vehicles within the work zone area will send their speed data to the RSU. Then, the prevailing speed of the platoon in the work zone will be estimated. This information will then be sent back to the OBUs of the vehicles that are within the work zone or approaching the work zone. The speed control points are distributed along the work zone and will collect the speed information of the vehicles around it and pass the speed information of the next points to the subject vehicle in real-time. In this way, the drivers will be prepared for deceleration if the speed in the work zone is reduced dramatically.

d. Speed Limit Warning

This warning strategy is shown as “1.d” in Figure 9. It is to enforce the speed limit for any highway sections and is not specifically for work zone section. The OBU of the vehicle is constantly sending the speed information to the RSU. If the speed is higher than the speed limit of the highway, the RSU will send the warning information back to the OBU and a voice warning will be triggered in the vehicle.

For the in-vehicle warning system described above, four different in-vehicle voice warning messages are created and recorded, which are summarized in Table 2.

Table 2 Four Different Types of Voice Warning Designed for VII based WZDWS

Voice Warning Message	Description
Work Zone Ahead	This message will be given when the subject vehicle is within a certain distance to the work zone
Stop Speeding. Speed Limit is XX MPH	This message will be given when the speed of subject vehicle is over the speed limit
Keep Safe Headway	This message will be given when headway between the subject vehicle and the vehicle in front of it is below a certain threshold
Prevailing Speed XX MPH	This message will be given when the subject vehicle passes one of the speed control points

Each of these voice messages is designed to address one kind of potential safety risk. The "Work Zone Ahead" message is used to remind the driver that there is a work zone ahead and be prepared for it. The "Stop Speeding" message is to help the subject vehicle conform to the speed limit. The "Keep Safe Headway" message is to reduce the risk of rear-end accidents as the voice warning will be given when the subject vehicle is too close to the vehicle in front of it. The "Prevailing Speed" message is to inform the subject vehicle about the current speed at the next speed control point.

2. Intelligent Dynamic Message Signs System

The Dynamic Message Signs will be installed in front of the work zone, which are highlighted in Figure 9 as 2.a and 2.b. The Dynamic Message Signs are controlled by the RSUs and will display the following two types of information sent from the RSUs.

a. Work Zone Condition information

Shown as "2.a" in Figure 9, the work zone condition signs will display information about the work zone, such as lane closure information and detour information. Figure 10 and 11 demonstrate the two typical signs, which will be used in turn.

Figure 10 Work Zone Presence Sign

Figure 11 Lane Closure Information Sign

b. Traffic Condition Signs

Shown as “2.b” in Figure 9, the traffic condition signs will display the prevailing speed within the work zone (which is the average speed of all the vehicles in the work zone) so that the driver will know the safe speed for passing through the work zone. Figure 12 shows the designed Dynamic Message Signs (DMS) for different prevailing speed conditions.

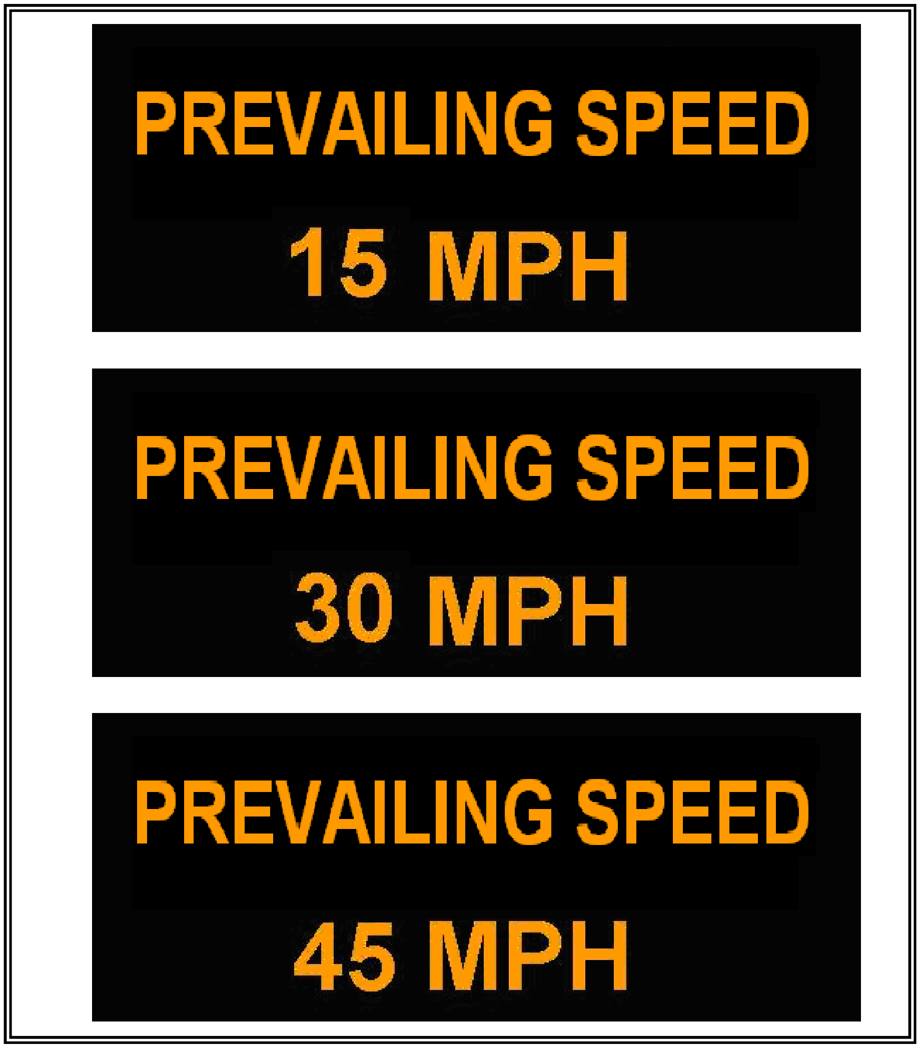


Figure 12 Prevailing Speed Sign

CHAPTER 4: METHODS FOR SYSTEM PERFORMANCE EVALUATION

This chapter is to introduce the methods for evaluating the effectiveness of the proposed VII technology based driver warning systems. Two different methods were used: 1) <u>driving simulator-based experiments</u> to test the driving performance of the participants driving with or without the assistance of the warning system, and 2) <u>survey</u> to solicit the participants' opinions about the proposed driver warning system after they go through the driving experiments.

4.1 Driving Simulator-based Experiments

4.1.1 Design of Driving Scenario

- *Scenarios design for RHDWS*

To investigate the application of the VII technology for preventing run-off-road collision (ROR), two driving scenarios were created in the simulator: (1) <u>the baseline scenario</u>: driving a vehicle without any warning system on a two-lane, rural highway and (2) <u>the study scenario</u>: driving a vehicle with the designed RHDWS on the same rural highway. As shown in Figure 13, both the baseline scenario and the study scenario were designed as a circular, two-lane rural highway.

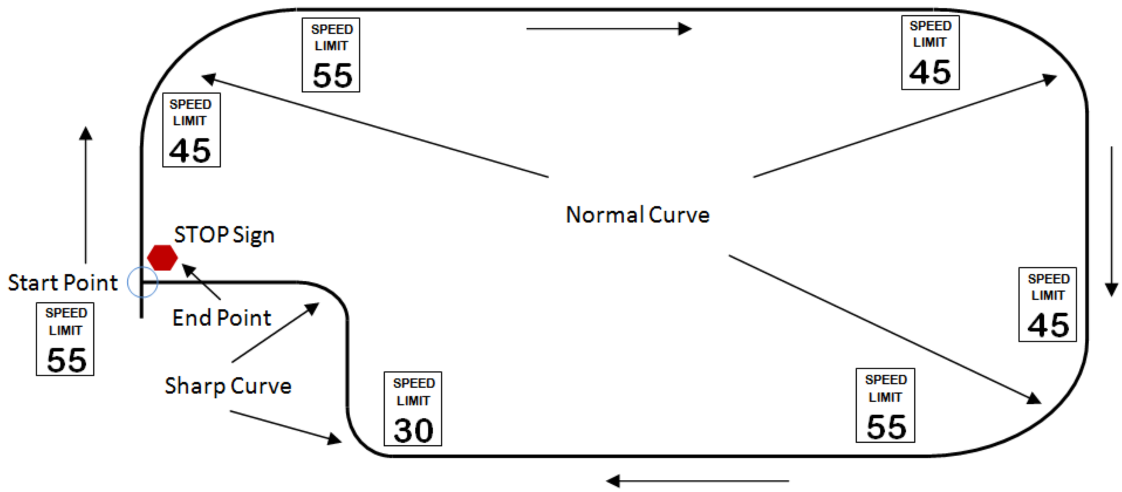


Figure 13 Schematic Map of Travel Route for Testing RHDWS

The travel route included three normal curves (45^{O}/200 meters) with a speed limit of 45 MPH and two sharp curves (45^{O}/50 meters) with a speed limit of 30 MPH. The speed limit on the straight segments of the roadway was 55 MPH. There were static message signs along the roadway to show the speed limit information to the drivers in both scenarios. The drivers started at the designated starting point, drove their vehicles around the designated circular roadway, and stopped at the specified stop sign (see Figure 13).

- *Scenarios design for HLCWS*

To evaluate the performances of developed HLCWS, two driving scenarios were created in the simulation experiments: (1) the baseline scenario: driving a vehicle without any warning system on a three-lane urban highway and (2) the study scenario: driving a vehicle with an on-board HLCWS on the same urban highway. Both scenarios were designed in a circular highway as shown in Figure 14. The total length of this route is eight miles. The traffic volume on this roadway is about 1400 vphpl, and the speed limit is 65 MPH. Under such traffic conditions, i.e., heavy volume and high speed, making lane changes becomes a daunting task. For each test scenario, participants were asked to finish one trip around this circular roadway. To ensure that lane changes would occur during the testing, the drivers were told that they had to arrive at eight destinations that were located on different sides of the roadway. These eight destinations were

McDonald's, Burger King, Texas Southern University, Starbucks, the Museum, Wal-Mart, a specific gas station, and NASA. The travel route and the location of these eight destinations are presented on the map in Figure 14. In each scenario, participants started from start point A and completed 16 lane changes in order to arrive at the eight destinations.

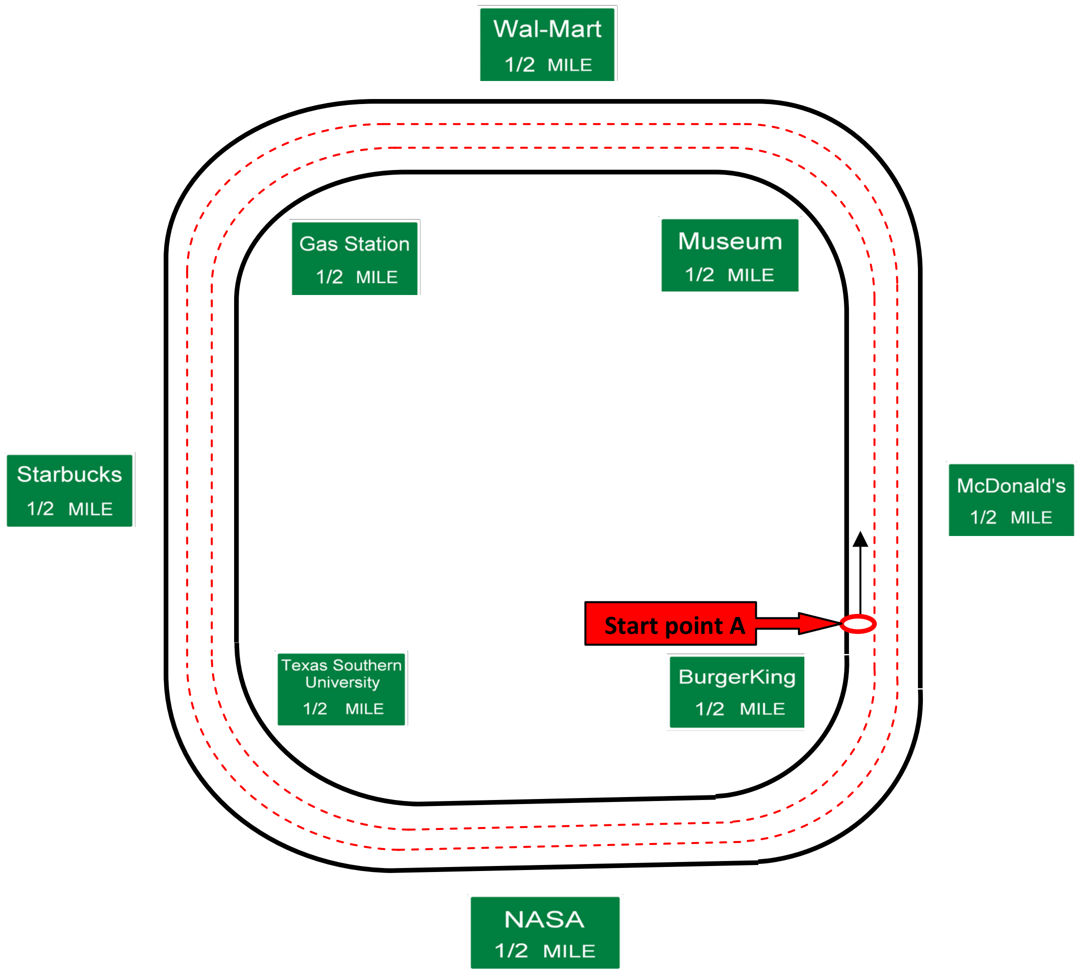


Figure 14 Schematic Map of Travel Route for Testing HLCWS

- *Scenarios design for WZDWS*

To compare the performance of the proposed VII-based work zone warning system with existing work zone safety control measures, following three types of scenarios are designed for testing in driving simulator environment: 1) the baseline scenario; 2) comparison scenario; and 3) study scenario. For the baseline scenario, the traditional safety control measure, static warning sign is used to inform the drivers that there is a work zone ahead. Figure 15 shows the layout of the baseline scenario.

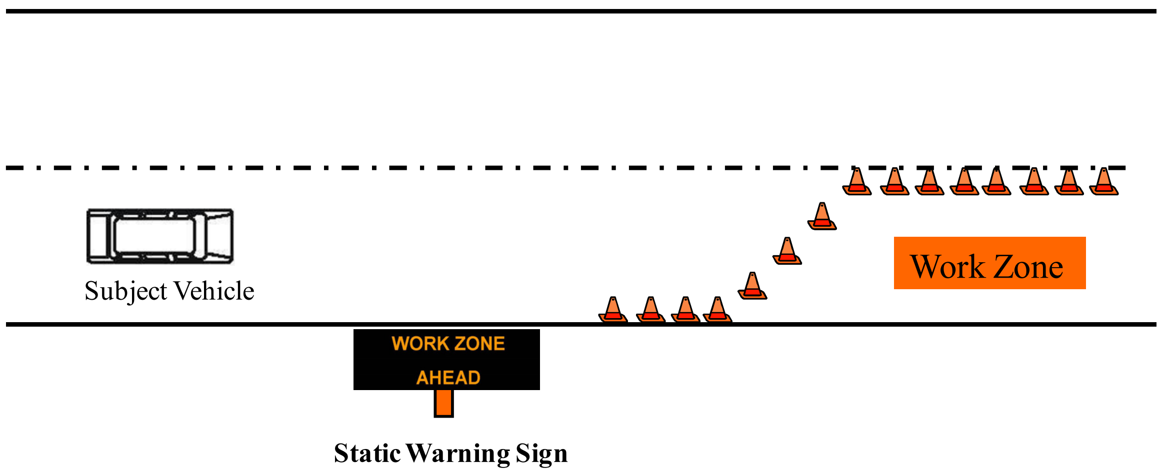


Figure 15 Layout of the Baseline Scenario

For the comparison scenario, the work zone safety control measures include a static warning sign, a flashing arrow sign and also police enforcement. Figure 16 shows the layout of the comparison scenario. It represents the current prevailing work zone safety control measures.

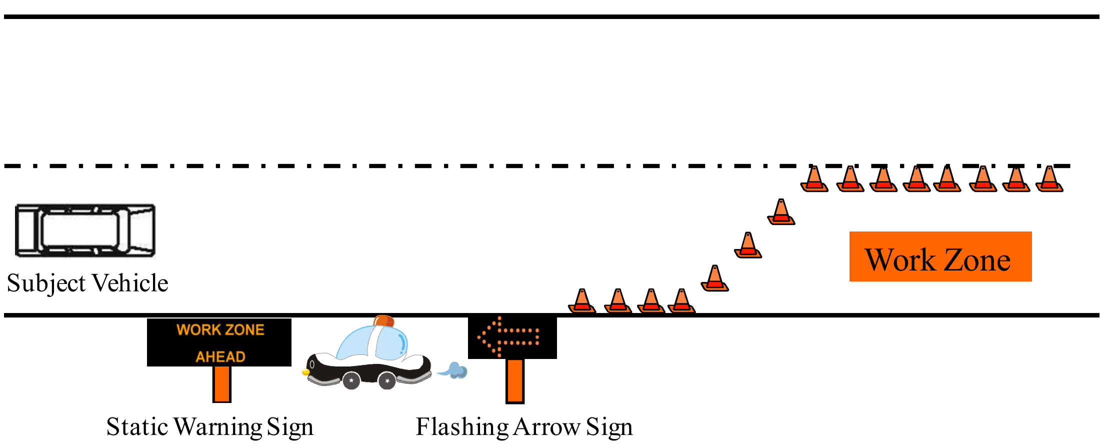


Figure 16 Layout of the Comparison Scenario

For the study scenario, the proposed VII based work zone collision prevention system is fully implemented. The layout of the study scenario is already shown in Figures 9. This scenario will implement the proposed VII based work zone collision prevention system introduced in the section 3.3 “Design of VII based WZDWS”, which include the in-vehicle driver warning system and the intelligent dynamic message sign system.

For each type of scenario, there will be two layouts, one is the one lane closure scenario (See Figure 17), and the other is the one side closure scenario where the traffic in one direction will be diverted to the opposing lane (See Figure 18). As a result, a total of six different scenarios (2 layouts × 3 scenarios for different types of work zone traffic control measures) have been built for testing.

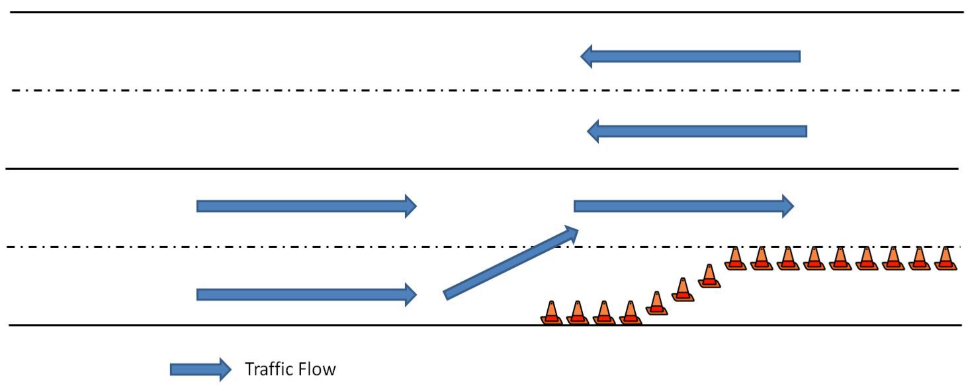


Figure 17 One Lane Closed Work Zone Layout

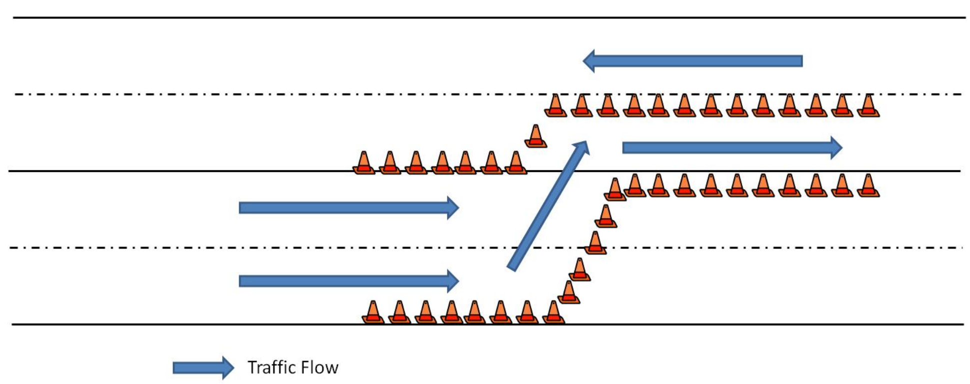


Figure 18 One Side Closed Work Zone Layout

4.1.2 Experimental Procedure

To access the safety effectiveness of the designed driver warning system, driving simulator-based experiments were performed.

- *Participants*

Thirty people were recruited for the driving simulation experiment. They were classified by their genders and by driving experience. The demographics of the people are presented in Table 3.

Table 3 Demographics of Study Participants

Driving Age	Gender		Total
	M	F	
<1 yr (23%)	1	6	7
1 to 3 yr (30%)	5	4	9
>3 yr (47%)	10	4	14
Total	16	14	30

.

- *Practice Session*

The practice session is primarily designed to acquaint the test subjects with driving in the simulator. The test subjects can become familiar with driving in such environment after the practice session. When they feel comfortable with driving the simulator, they will tell the test administrator and the real test will begin after that. Figure 19 shows a subject driving in the practice session's scenario.

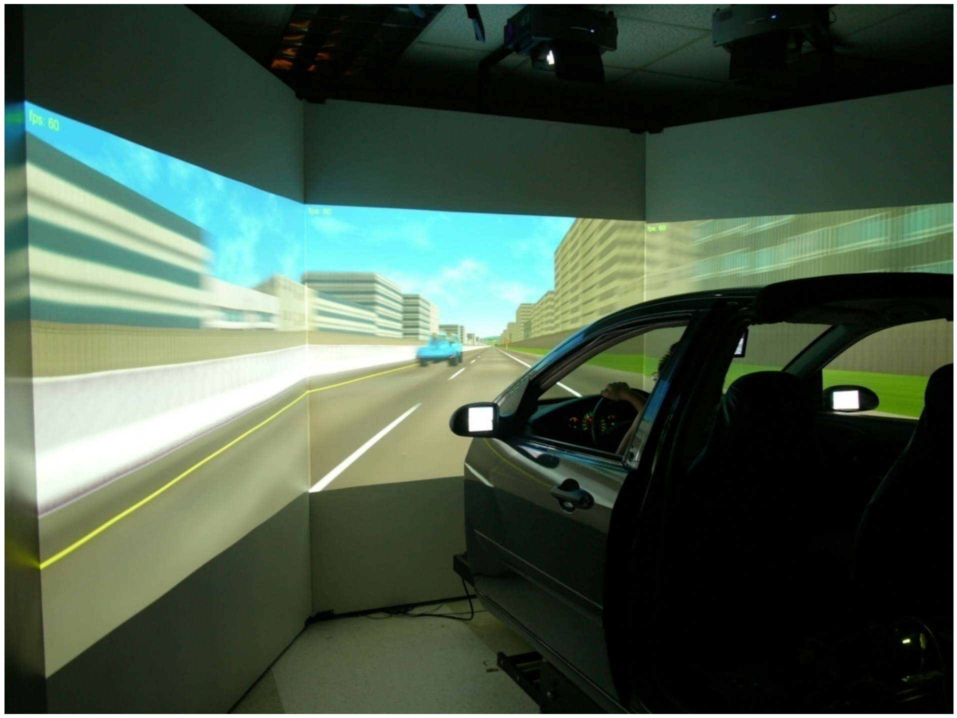


Figure 19 Practice Session in an Urban Area

- *Testing Scenario*

After the practice scenarios, the participants drove in the seven test scenarios: two for testing the RHDWS (including the baseline and the study scenarios), two for testing HLCWS (including the baseline and the study scenarios), and three for testing WZDWS (including the baseline scenario, the comparison and the study scenario for one type of work zone layout). The order of these test scenarios was determined randomly.

4.2 Survey

After the experiments, the participants were surveyed to obtain their opinions of the driving warning system. They were asked to complete three surveys for three driver warning systems. All the surveys consisted of two parts. The first part was to collect detailed information about the drivers, including:

- Test Date

- Driver’s Name
- Driver’s Gender
- Driver’s Age
- Driver’s Driving Experience

The second part was to solicit the drivers’ opinions of the three developed VII-based driver warning systems by asking some general questions as show in Tables 4, 5, 6.

Table 4 Survey of Rural Highway Driver Warning System

Date:

First Name: Middle Initial: Last Name:

What is your gender?

☐ Male ☐ Female

What is your age?

☐ Under 21 ☐ Between 22 to 32

☐ Between 32 to 59 ☐ Greater than 60 years old

If you have driver license, how long have you had the driver license?

☐ Less than 1 year ☐ 1 to 3 years ☐ More than 3 years

Question 1. Do you think the driver warning system is helpful for preventing ROR crashes?

Warning Functions	Extremely Helpful	Very Helpful	Helpful	A Little Helpful	Not Helpful At All
Speed Limit warning	☐	☐	☐	☐	☐
Curve Ahead warning	☐	☐	☐	☐	☐
Lane Departure warning	☐	☐	☐	☐	☐

Question 2. Are you used to this warning system?

☐ No, it is hard for people to accommodate to it

☐ Yes, but it will take some time

☐ Yes, it is easily for people to accommodate to it

Question 3. Comments for the Driver Warning System:

Table 5 Survey of Highway Lane Change Warning System

Date:
First Name: **Middle Initial:** **Last Name:**
What is your gender? ☐ Male ☐ Female
What is your education level? ☐ High School Diploma or Less ☐ Undergraduate ☐ Graduate
What is your age? ☐ Under 21 ☐ Between 22 to 32 ☐ Between 32 to 59 ☐ Greater than 60 years old
Do you have a driver license? ☐ YES ☐ NO
If you have driver license, how long have you had the driver license? ☐ Less than 1 year ☐ 1 to 3 years ☐ More than 3 years
Question 1. **Do you think the warning messages are helpful for preventing lane change crashes?** ☐ Extremely Helpful ☐ Very Helpful ☐ Helpful ☐ A Little Helpful ☐ Not Helpful At All ***Question 2.*** **Is this warning system easy for people to accommodate?** ☐ No, it is hard for people to accommodate to it ☐ Yes, but it will take some time ☐ Yes, it is easily for people to accommodate to it ***Question 3.*** **Comments for the Highway Lane Change Warning System:**

Table 6 Survey of Work Zone Driver Warning System

Date:

First Name: **Middle Initial:** **Last Name:**

What is your gender?

☐ Male ☐ Female

What is your education?

☐ High School Diploma or Less ☐ Undergraduate ☐ Graduate

What is your age?

☐ Under 21 ☐ Between 22 to 32

☐ Between 32 to 59 ☐ Greater than 60 years old

Do you have a driver license?

☐ YES ☐ NO

If you have driver license, how long have you had the driver license?

☐ Less than 1 year ☐ 1 to 3 years ☐ More than 3 years

Please rate the effectiveness of different traffic control devices and/or voice warning systems in terms of preventing accidents

Traffic Control Device/ Warning System		Extremely Helpful	Very Helpful	Helpful	A Little Helpful	Not Helpful At All
Static Signs		☐	☐	☐	☐	☐
Flashing Arrow Signs		☐	☐	☐	☐	☐
Police Enforcement		☐	☐	☐	☐	☐
Voice Warning	Work Zone Ahead	☐	☐	☐	☐	☐
	Speed Limit	☐	☐	☐	☐	☐
	Keep Safe Headway	☐	☐	☐	☐	☐
	Prevailing Speed	☐	☐	☐	☐	☐

Are you used to the warning system?

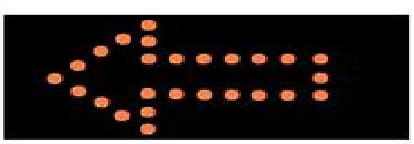
☐ No, it is hard for people to accommodate to it

☐ Yes, but it will take some time

☐ Yes, it is easily for people to accommodate to it

Comments for the Highway Curve Warning System:

The following two types of signs are designed to tell the drive to merge left. Please select the one that you think is easier to understand



4.3 Devices, Techniques, and Tools

4.3.1 Hardware

The DriveSafety DS-600c simulator was used for designing and testing the driver warning system in our study. This simulator is a fully-integrated, high-performance, high-fidelity driving simulation system that can effectively approximate real-world driving conditions. It provides multi-channel audio/visual systems, 180°, 240°, 300°, and 360° wrap-around display options, full-width automobile cab including windshield, driver's and passengers' seats, center console and dash, full instrumentation, control-loaded steering, braking and acceleration, and mini-LCD rear-view mirrors, and real-time motion simulation through DriveSafety's Q-Motion (tm) platform. The detailed introduction of the simulator in both hardware and software sides are to be presented here.

The driving simulator at Texas Southern University is composed of five hardware components: 1) the cab, 2) the projectors, 3) three large screens, 4) a set of computers for simulation, and 5) a computer for scenario creation (Figure 20 and Figure 21).

- *Cab.* The cab is outfitted with computers, potentiometers, and torque motors that are connected to the accelerator, brakes, and steering. It also features full stereo audio, full instrumentation, and fully interactive vehicle components, all of which provide the realistic feeling of driving.
- *Projectors, Screens and Computers.* The cab is connected to a set of computers for simulation (computers on the rack) that consists of one host computer and six image generation computers. The host computer had the software Vection installed, which are for Backend/Simulator Functionality and runs on Fedora Core 3.0 (Linux system). The six image generation computers generate driving scenes and send them to three high-resolution projectors and the rear and side mirrors in the cab. Through the projectors, the scenes project to three larger screens.
- *Workstation.* The computer for scenario creation is the major workstation for creating various driving scenarios. The software applications, HyperDrive and Dashboard, were installed. HyperDrive is for creating scenarios and Dashboard is for transferring scenarios and controlling simulation.

The following figures show the principle of all the equipment and their locations at Texas Southern University.

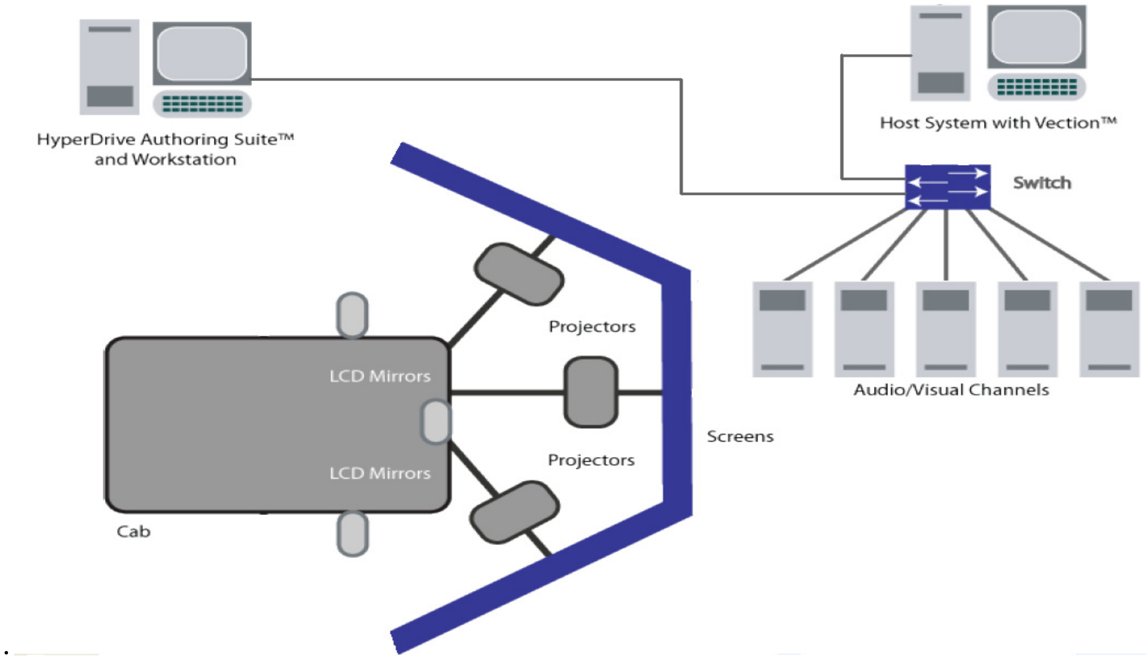


Figure 20 Schematic Diagram of Driver Simulator Components

Figure 21 Driver Simulator Components

4.3.2 Software

To design the driving warning scenarios in the driving simulator environment, three simulator-related software packages are used:

- HyperDrive. This software delivers a Windows-based, drag-n-drop software interface allowing non-technical users the ability to design, build, execute, and analyze driving scenarios without technical or engineering assistance. Driving scenarios include basic autonomous traffic as well as custom-defined scripted vehicle actions and reactions. Figure 22 shows the interface of the HyperDrive software. Figure 23 shows the script interface of HyperDrive.

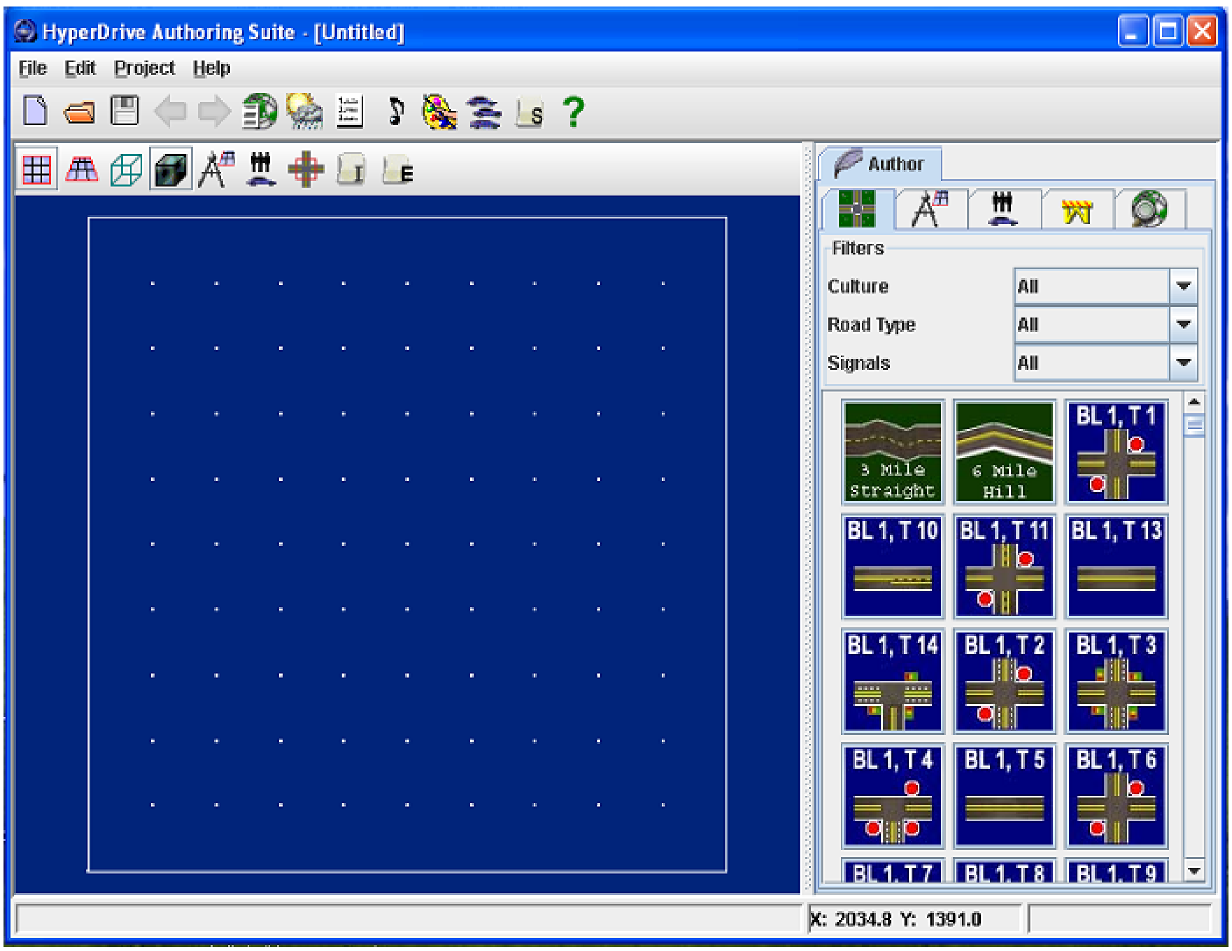


Figure 22 HyperDrive Interface.

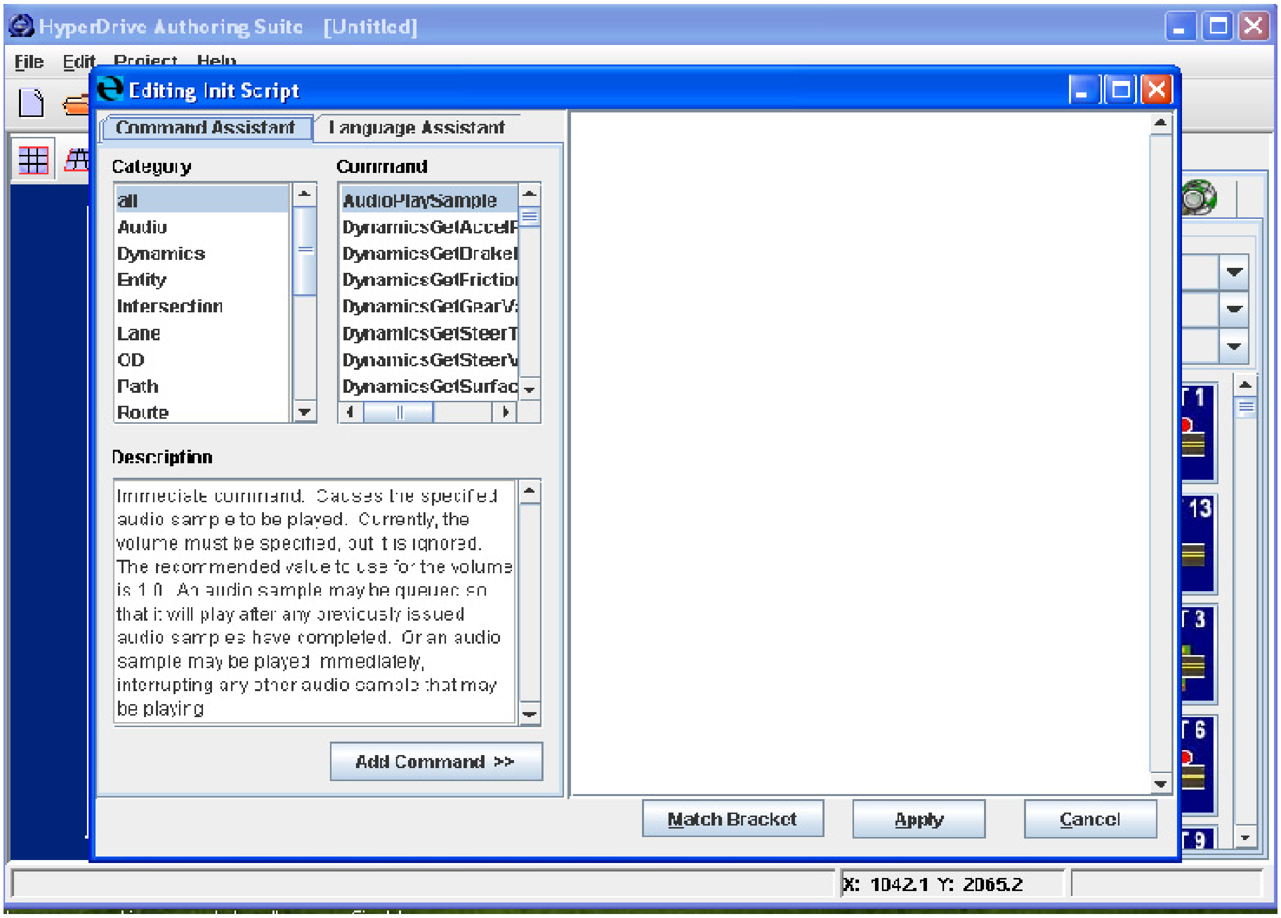


Figure 23 Script Frame in HyperDriver.

- Vection. This software is a deterministic real-time simulation system. It is a run-time software package that includes advanced vehicle dynamics, scenarios control with both scripted and autonomous traffic simulation, flexible data collection, audio and visual subsystems, and integrated support for cab instrumentation, control loading, and motion platform control. Vection provides an extremely powerful environment for providing realistic driving simulation experiences and measuring the desired results.
- Dashboard. This software acts as a connector between HyperDrive and Vection. It is comprised of several different sections - a simulator section, a component section, a project management section, and a simulator control section. Figure 24 shows the interface of the Dashboard software.

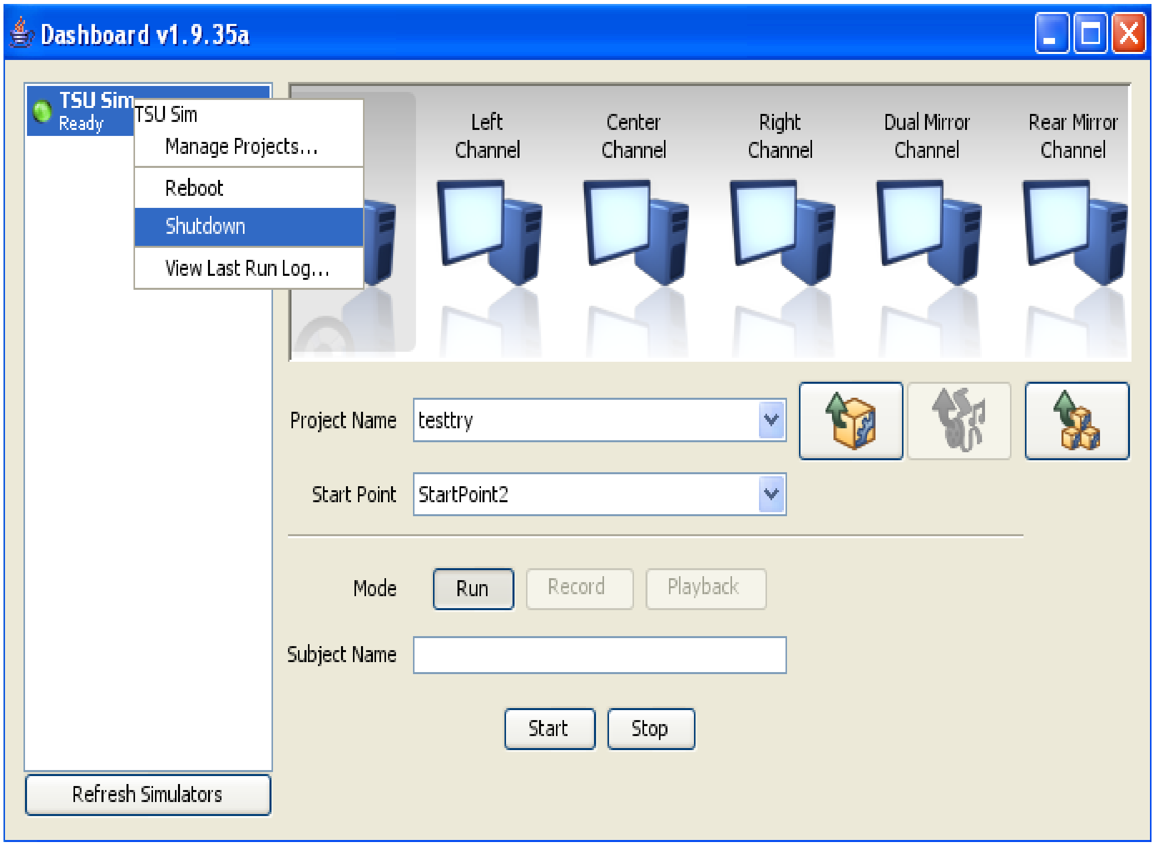


Figure 24 Dashboard Interface.

In addition, this research also used several mathematical and statistical techniques as well as some computing and coding tools. These included Microsoft Excel , SPSS, and Tcl Language, etc.

- Microsoft Excel is one of the most widely used computer software in data analysis. This software was used to process the outputs of the tests and calculate the measures of effectiveness (MOES);
- SPSS is a computer statistics program for data management and analysis. SPSS was used to compare the means of MOES for two groups of outputs collected from the tests;
- Tcl Language: The word "Tcl" is originally from "Tool Command Language". It is a scripting language created by John Ousterhout. This scripting language was used in the HyperDrive to script the three types of warning functions: speed limit warning, curve ahead warning and lane departure warning.

CHAPTER 5: EVALUATION RESULTS

In this chapter, the evaluation results of both driving simulator-based experiments and survey for the three proposed driver warning systems are presented and discussed.

5.1 Evaluation Results for RHDWS

5.1.1 Measure of Effectiveness from Simulator-Based Experiments

After conducting the driving simulation experiments, the participants' driving performance under different driving scenarios were evaluated based on the outputs of the driving test. In this study, the following measure of effectiveness (MOE) was derived for analyzing driving performance.

- *Number of Critical Events and Number of ROR Events*

The definitions of critical events and ROR events are presented in the system design section (Figure 4). During the tests, the Deviation Distance (*DD*) of the subject vehicle was collected every second. Based on these data, if any critical events or ROR events were detected, they were counted to obtain the total number of critical events and ROR events for all the tests. Greater numbers of critical events and ROR events indicate greater risk during driving.

- *Maximum Deceleration:*

Deceleration is a good surrogate measure for safety research. It can indicate the potential severity of the conflict event *(28)*. During the testing, the deceleration rate of the subject vehicle was collected every second. The maximum deceleration was recorded for assessing the driving performance of the participants in both scenarios.

- *Speed Conformity Percentage*

Speed conformity percentage is defined as the percentage of time that the subject vehicle is traveling at a speed that is lower than the speed limit. During the tests, the speed of the subject vehicle was collected every second and compared with the posted speed limit. The number of times in which the speed of the subject vehicle is less than the speed limit was determined. When the tests were completed, the speed conformity percentage was determined using the following equation:

$$Speed\ Conformity\ Percentage = \frac{\#\{S_t < S_{Limit}\}}{Total\ \#\ of\ \ Data\ Collection\ Points} * 100\% \qquad (11)$$

where S_t is the speed of subject vehicle at time t, and

S_{Limit} is the speed limit of the road section.

5.1.2 Analysis of Drivers' Performance

The MOEs defined above were collected from the experiments for each participant. By comparing the MOEs from the baseline and the study scenarios, the impacts of the driver warning system on the drivers' driving performance were assessed. The averages of the MOEs for both driving scenarios, i.e., the baseline and the study scenarios, are presented in Table 7. For comparing the MOEs from both driving scenarios, the paired t test, a statistical method for comparing the means of two groups of related samples, was used. It is because each participant's driving performances in the two driving scenarios were related. The results of the paired t test are also presented in Table 7. It shows that the average number of critical events in the study scenario was significantly less than in baseline scenario ($t = 1.918, P = 0.065$). This result indicates that the driver warning system can significantly reduce the critical events by as much as approximately 21%. The average number of ROR events was drastically decreased in the study scenario compared with that in the baseline scenario ($t = 5.248, P = 0.000$). This shows that the driver warning system has improved the driver's safety by decreasing the ROR crashes by approximately 71%. The difference between maximum deceleration in the baseline scenario and in the study scenario was also very significant ($t = -2.124, P = 0.042$). The results show that the system decreased the maximum deceleration by approximately 70%. It indicates that the driver warning system contributed to smoother driving on the curvy highway, thereby improving safety on such a roadway. Statistical analysis results also proved that the speed limit conformity percentage of the study scenario is significantly higher than that in the baseline scenario ($t = -10.891, P = 0.000$) which also indicates that the driver warning system can improve the drivers' safety by preventing speeding.

Table 7 Paired T-test Evaluation Results for the RHDWS

MOEs	Scenarios	Average of MOEs	Improved Percentage	t-value	P-value
Number of Critical Event	Baseline	4.07	20.64%	1.918	0.065
	Study	3.23			
Number of ROR Event	Baseline	3.77	70.82%	5.248	0.000
	Study	1.10			
Maximum Deceleration	Baseline	-14.07 m/s	69.97%	-2.124	0.042
	Study	-4.225 m/s			
Speed Conformity rcentage	Baseline	44.305	88.72%	-10.891	0.000
	Study	83.612			

5.1.3 Analysis of Survey Results

Each of the participants completed a survey after finishing the two test scenarios. The survey form is shown in Table 5. For *Question 1*, the participants scored the three warning functions according to their effectiveness in preventing ROR crashes. “Extremely Helpful” is indicated by the highest score of five, and “Not Helpful At All” is indicated by the lowest score of one. Figure 25 presents the average score of the three different warning functions. The curve ahead warning received the highest score of 4.3. The scores of the lane departure warning and the speed limit warning were 3.93 and 3.97, respectively. These results indicate that the drivers felt that the curve ahead warning was the most useful in preventing ROR crashes.

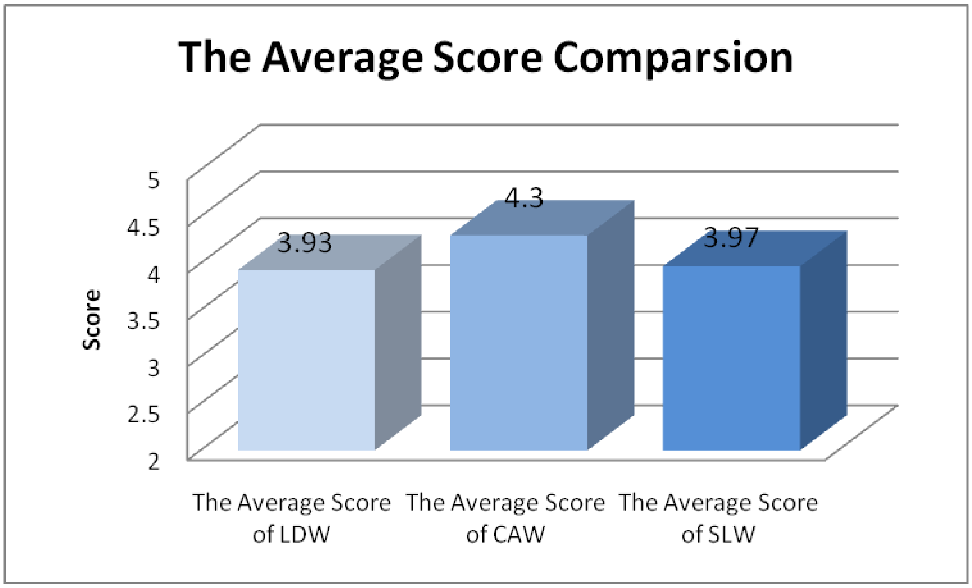


Figure 25 Comparison of Average Score forDifferent Warning Functions

The survey result for *Question 2*, "Whether this driver warning system is easy for people to accommodate?" is presented in Figure 26. It was found that approximately 53% of the participants thought the driver warning system was easy for them to use. Approximately 13% of the participants thought that this system was hard for people to use. This result indicates that the driver warning system should be acceptable to most drivers.

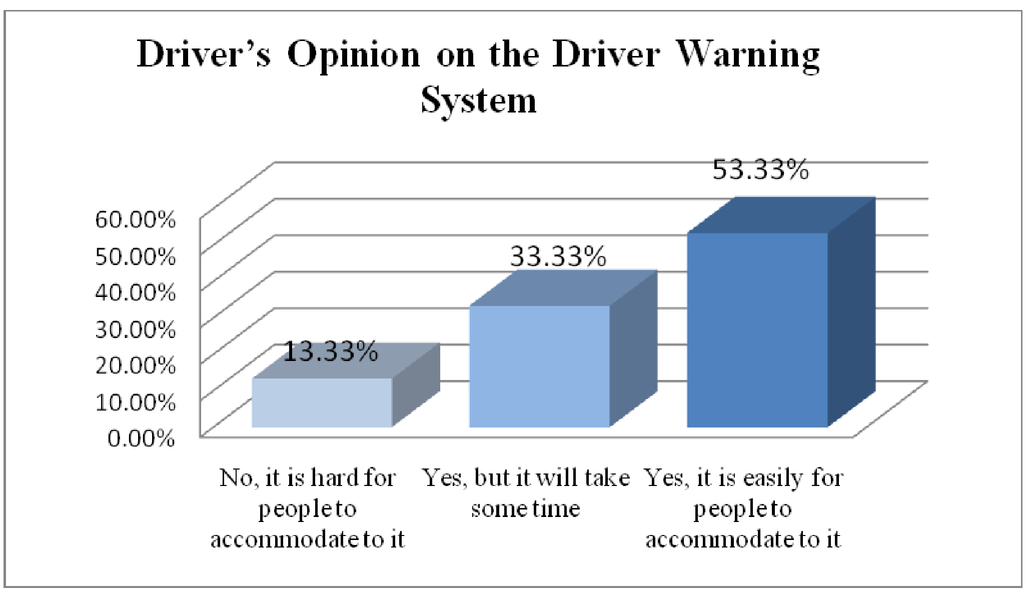


Figure 26 Driver's Opinion of the Driver Warning System

5.2 Evaluation Results for HLCWS

5.2.1 Measure of Effectiveness from Simulator-Based Experiments

After conducting the driving simulation experiments, the participants' driving performances under different driving scenarios were evaluated. In this study, the following measure of effectiveness (MOE) was used for analyzing the drivers' performances.

- *Number of Lane Change Collision*

The number of the lane change collisions that occurred during the driving test. As we mentioned in the experiment design section, there would be 16 lane changes in each scenario. During the testing, if, when making a lane change, the subject vehicle collided with a vehicle in the destination lane, this collision was defined and recorded as a "lane change collision."

- *Number of Critical Events:*

Similar to the RHDWS, the performance of the HLCWS was also evaluated by the number of critical events. In this study, there are two types of critical events that are defined by two different measures: a) the Time-To-Collision (*TTC*), and b) Deceleration.

- *Number of critical events defined by TTC*

TTC is defined as the time required for two vehicles to collide if they continue at their present speed and on the same path. It is an effective measure for safety performance analysis. Basically, a lower value of TTC indicates a greater likelihood of a collision. In this study, TTC was measured between the subject vehicle and the nearest vehicle in the destination lane and was collected during a short time period after the subject vehicles made lane changes. TTC can be calculated by the following equation (See Figure 27 for the notations used in the equation).

$$TTC = \min\left(\frac{d_2}{V_S - V_L}, \frac{d_1}{V_F - V_S}\right) \tag{12}$$

d_1: distance between subject vehicle *S* and vehicle *F*

d_2: distance between subject vehicle *S* and vehicle *L*

V_F: vehicle *F*'s velocity

V_L: vehicle *L*'s velocity

V_S: subject vehicle's velocity

The TTC value was determined each time a test driver made a lane change. If the TTC value is smaller than 2.5*s* (*TTC* < 2.5*s*) *(29),* a critical event was detected and recorded.

- *Number of critical events defined by deceleration rate*

As we mentioned in the warning strategy section, after the subject vehicle *S* changes to the destination lane, there are two possible risky situations as demonstrated in Figure 8. In *Situation 1*, vehicle *F* will decelerate in order to avoid a collision with subject vehicle *S.* The deceleration rate of vehicle *F* will be recorded. In *Situation 2*, subject vehicle *S* will decelerate to avoid a collision with vehicle *L*. The deceleration rate of vehicle *S* will be recorded. If the recorded deceleration rates during lane changes were greater than 2.5 m/s^2 *(30),* a critical event was identified.

These MOEs, i.e., the number of lane change collisions and different types of critical events, were collected during the driving simulation experiments for both scenarios.

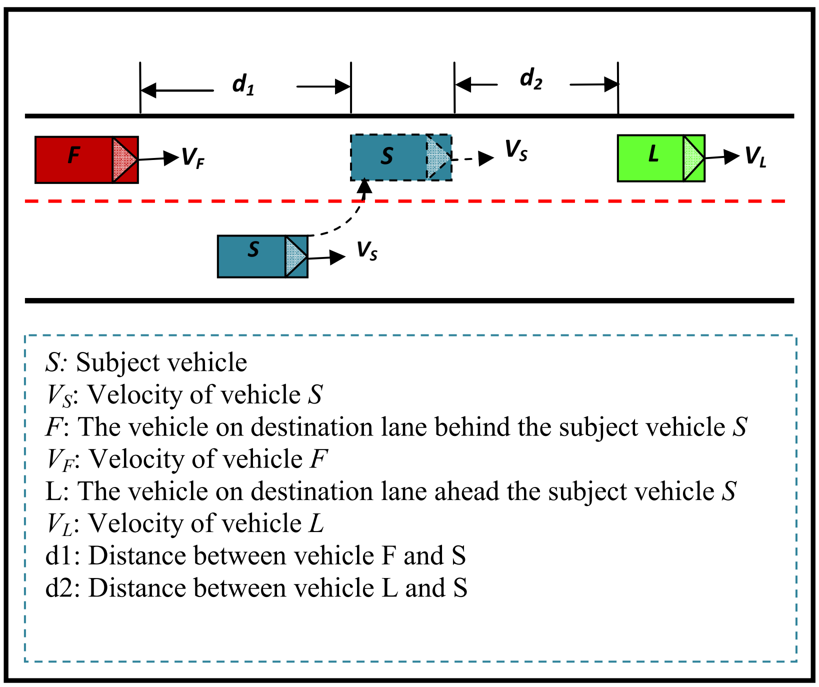


Figure 27 Deceleration Events during the Lane Change

5.2.2 Analysis of Driver's Performance

The averages of the MOEs collected from the experiments for both driving scenarios, i.e., the baseline and the study scenarios, are presented in Table 8. By comparing the MOEs for both driving scenarios, the impacts of the HWLCS on the drivers' performances were assessed, and this was done by using the paired t test. In this study, the paired t test is applied to compare the means of the three MOEs (i.e. the Number of Lane Change Collisions, the Number of Critical Events by TTC and the Number of Critical Events by Deceleration) of the same participant collected in both the baseline scenario (without the use of HLCWS) and the study scenario (with the use of HLCWS). Therefore, data for the test is paired by the participates and the test results show if the use of the HLCWS will cause significant difference in the participants' driving performances during the lane changes or not.

Paired t Test Results. The results of the paired t tests are also presented in Table 8. The results show that the average number of lane change collisions in the study scenario were significantly less than the number in the baseline scenario ($t = 4.54$, $P < 0.0001$). This result indicated that the HLCWS can significantly reduce collisions caused by lane changes. In addition, the average numbers of two critical events were all significantly reduced in the study scenario compared with the numbers in the baseline scenario (P values are all less than 5%). This result further proved that the HWLCS helped drivers make lane changes safely and that it could significantly reduce the risk of accidents associated with lane changes.

Table 8 Paired T-test Evaluation Results for the HLCWS

MOEs	**Averages of MOEs**		**t value of paired t test**	**P value**
	Baseline Scenario	**Study Scenario**		
Lane Change Collision	0.8	0.17	4.54	<.0001
Critical Events Defined by TTC	2.63	1.77	2.12	<0.05
Critical Events Defined by Deceleratio	2.56	1.03	4.36	<0.01

5.2.3 Analysis of Survey Result

After driving in two test scenarios, each participant was asked to complete a survey form, shown in Table 5. The survey results for *Question 1,* "Do you think the warning messages are helpful for preventing lane-change crashes?" are summarized in Figure 28, which shows that 23.33% of the 30 participants think that the HLCWS was extremely helpful when making lane changes; 43.33% of participants said it was "Very Helpful;" 20% of participants said it was "Helpful;" 10% of participants said it was "A Little Helpful;" and only 3.33% of participants said it was "Not Helpful." Overall, more than 85% of the participants stated that the HLCWS was better than "Helpful." These results suggest that most drivers will benefit from the use of this HLCWS.

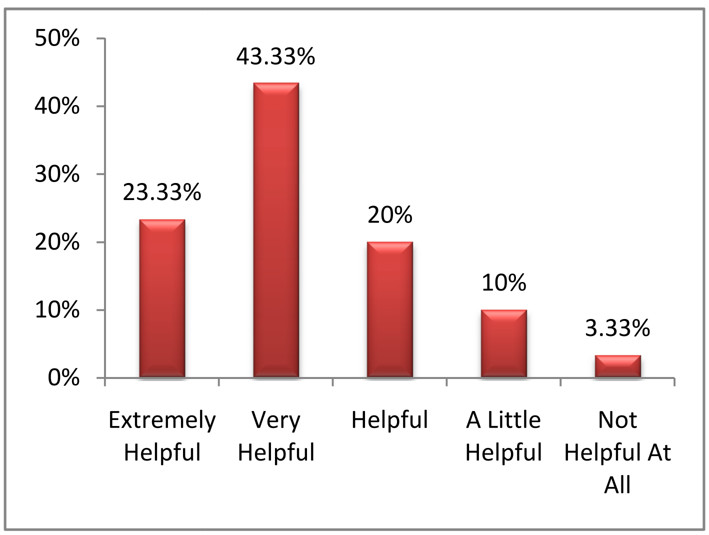


Figure 28 Drivers' Comments on HLCWS

The survey results for *Question 2* "Are you used to this warning system?" are presented in Figure 29. It was found that 63.33% of the participants stated that this HLCWS was easy for them to accommodate, whereas only 10% of the participants stated that this system was hard for people to use. These results indicate that the developed HLCWS may be accepted by most drivers.

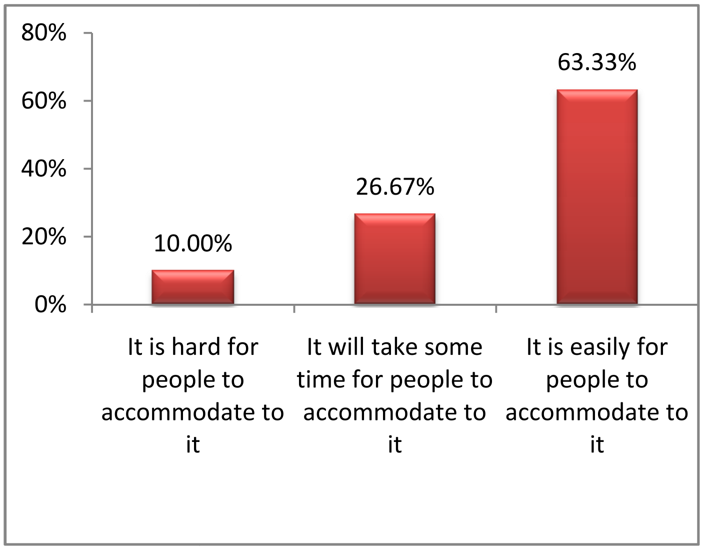


Figure 29 Drivers' Acceptance of HLCWS

5.3 Evaluation Results for WZDWS

5.3.1 Measures of Effectiveness from Simulator-Based Experiments

After conducting the driving simulation test, the participants' driving performance under various scenarios was evaluated based on the outputs of the experiments. Following MOEs are derived for comparing the driver's performance under different types of work zone scenarios.

- *Number of Collisions*

During the testing, if, the subject vehicle collided with another vehicle, this collision is identified and recorded in the driving simulator system.

- *Minimum Time-To-Collision*

Similar to the evaluation for HLCWS, TTC is used for the evaluation for WZDWS. Basically, a lower value of TTC indicates a greater likelihood of a collision. TTC in the work zone driving scenario are defined by following equation.

$$TTC = \frac{H_D}{V_S - V_A} \tag{13}$$

Where, TTC is the Time-To-Collision,

HD is the headway in distance,

VS is the velocity of the subject vehicle, and

VA is the velocity of the vehicle in front of the subject vehicle.

- *Number of Critical Events*

Critical events are defined by the TTC. Since low value of TTC indicates a risky situation, if TTC value is smaller than a specific threshold (3 seconds in this study), a critical event was detected and recorded.

- *Maximum Deceleration:*

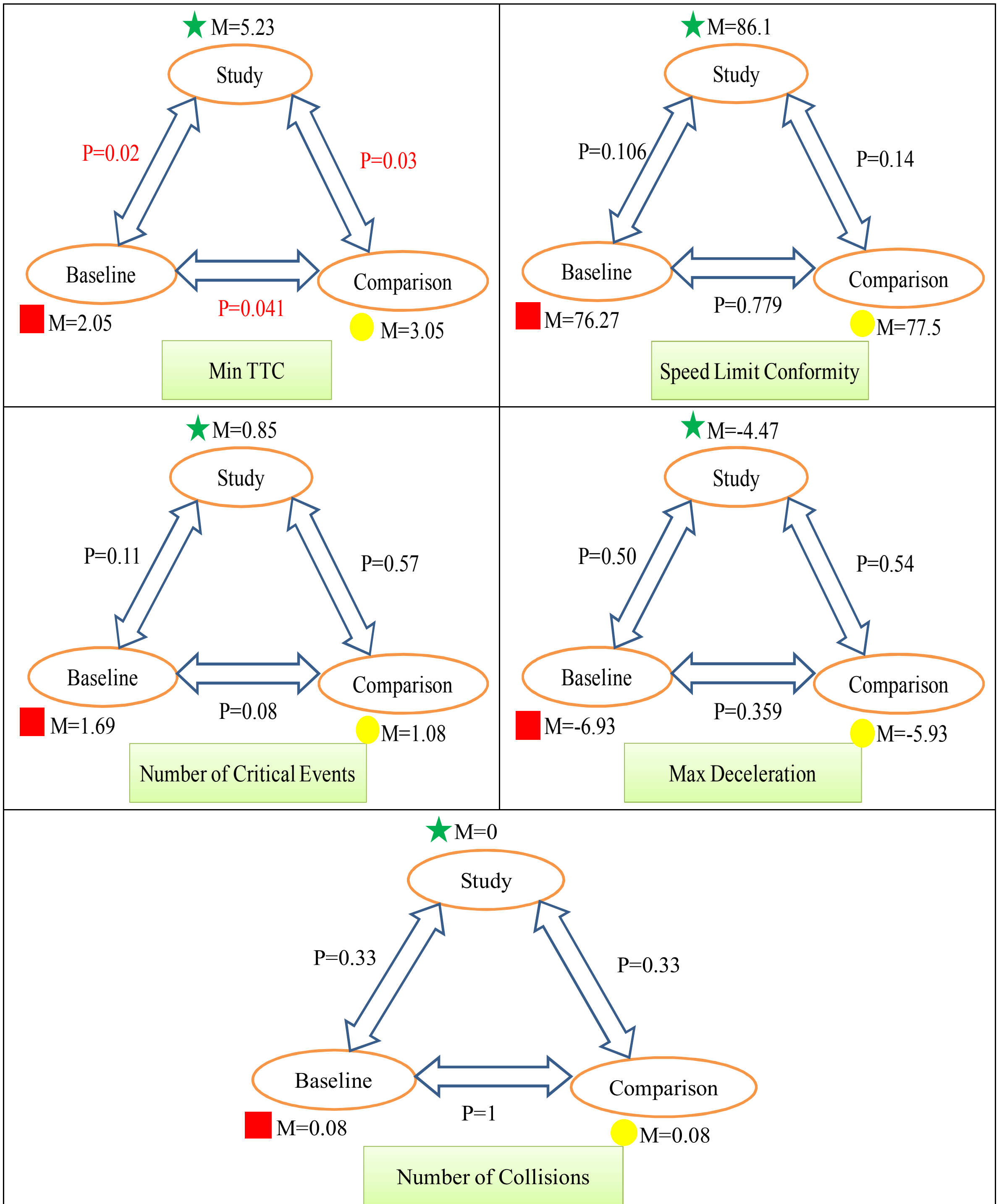
See definition in Section 5.1.1.

- *Speed Limit Conformity*

See definition in Section 5.1.1.

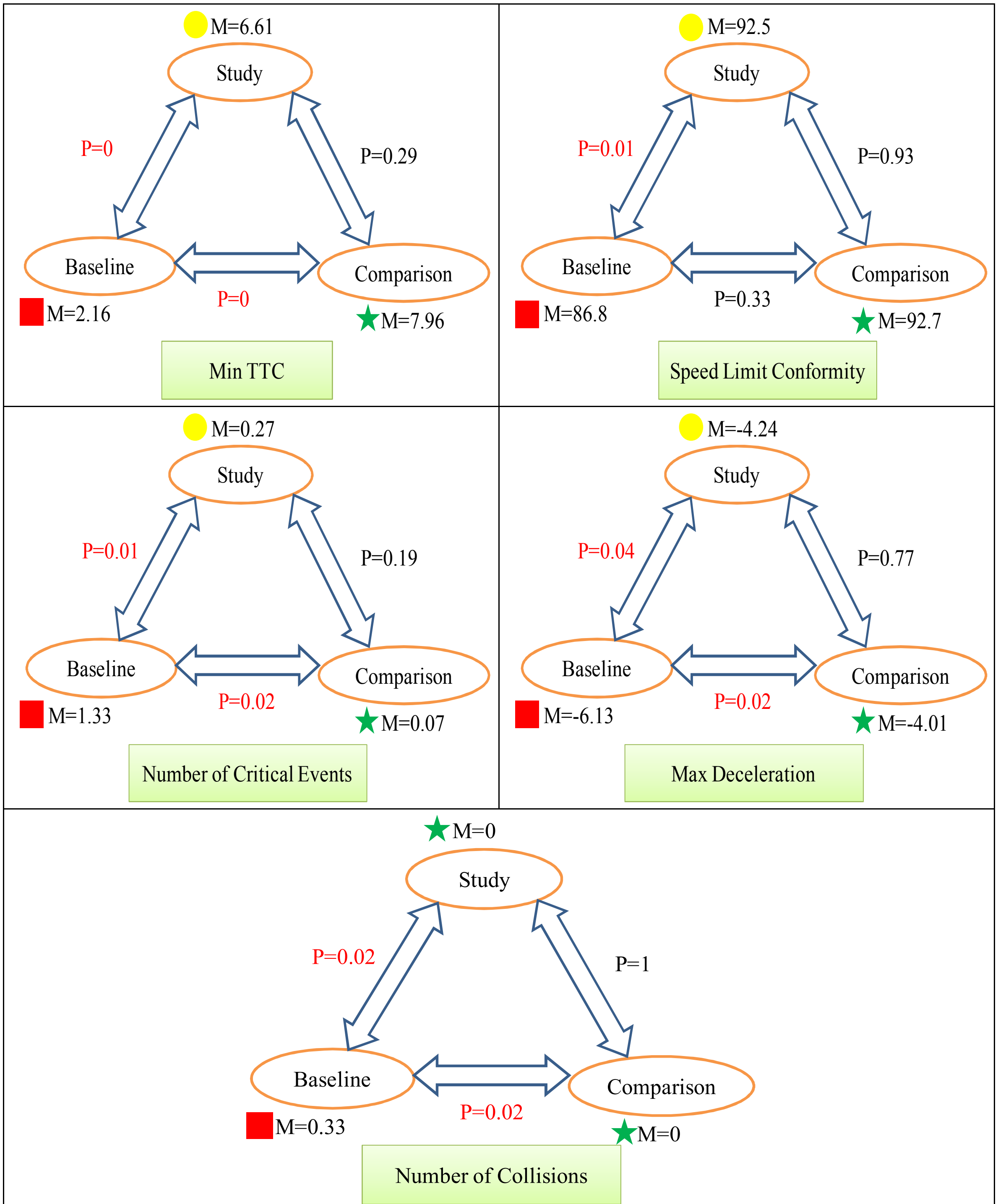
5.3.2 Analysis of Drivers' Performance

Based on the data collected during the simulator testing, five different types of MOEs are derived including Number of Collisions, Minimum Time-To-Collision, Number of Critical Events, Maximum Deceleration and Suggested Speed Limit Conformity. These MOEs are used to indicate the subjects' driving performance during different testing scenarios. Similar to the previous evaluation studies, Paired T-test is used to compare the driving performances in different testing scenarios. The results of Paired T-test are presented in Figure 30 and Figure 31.



Note: M: Mean of MOEs of Base, Comparison and Study Scenarios
P: P-Value of paired T-test, small P-value (<5%) indicates that the difference between means are statistically significant
★: Best safety performance; ●: medium safety performance; ■: worst safety performance

Figure 30 Mean and P-Value for Base, Comparison and Study Scenarios for Work Zone Layout 1



Note: M: Mean of MOEs of Base, Comparison and Study Scenarios

P: P-Value of paired T-test, small P-value (<5%) indicates that the difference between means are statistically significant

★: Best safety performance; ●: medium safety performance; ■: worst safety performance

Figure 31 Mean and P-Value for Base, Comparison and Study Scenarios of Work Zone Layout 2

From Figure 30 and Figure 31, it is found that the baseline scenario has the worst safety performance for all five MOEs. For Work Zone Layout 1, the MinTTC of the baseline scenario is significantly less than those of the comparison and study scenario, which indicates that the baseline scenario is not as safe as the other two scenarios. The Speed Limit Conformity of the baseline scenario is also less than those of the other two scenarios, which means that drivers are more likely to excess the speed limit in the baseline scenario. This can be viewed as a sign of a potential safety problem. The number of critical events and collisions are higher in the baseline scenario, too. The maximum deceleration is associated with the severity level of the potential conflicts. The higher the deceleration, the worse is the safety performance. The baseline scenario has the highest deceleration rate, which means that it has the worst safety performance. Similar observations can be found for Work Zone Layout 2. The poor safety performance of the baseline scenario is because of the lack of effective safety control measures at the work zone.

The safety performances of the comparison and study scenario vary among different work zone layouts and MOEs. For Work Zone Layout 1, there is a significant difference for the MOEs MinTTC and Speed Conformity. By comparing the means of these two MOEs, it is found that the study scenario is significantly better than the comparison scenario. For the other three MOEs, although the statistical test is not significant, the means of the study scenario is still better than the comparison scenario. In summary, for Work Zone Layout 1, the study scenario is better than the comparison scenario. However, for Work Zone Layout2, the situation is quite different. All the MOEs have no significant differences, which indicates that the VII warning systems have similar effectiveness as the prevailing traffic control measures used in the comparison scenario. This may due to the following reasons:

1. Different work zone layouts have different sight distances.

For Work Zone Layout 1 (See Figure 32), the sight of the subject vehicle is blocked by the queuing vehicles at the work zone. This makes it difficult for the drivers to know in advance that there is a work zone ahead in the comparison scenario with regular work zone control measures. That is why the VII based warning system shows its benefits in this scenario. However, for Work Zone Layout 2, the work zone is considerably larger than in Work Zone Layout 1. The sight distance for the work zone is much longer (See Figure 33), which means that the driver is able to see the work zone at a fairly advanced location and be prepared for possible slowdowns. Under this situation, the additional information, provided by the VII based WZDWS, will not be of much help for the driver. It may even distract the drivers in certain circumstances. That is why in Work Zone Layout 2, the subjects' driving performances in the comparison and study scenarios have no significant difference at all.

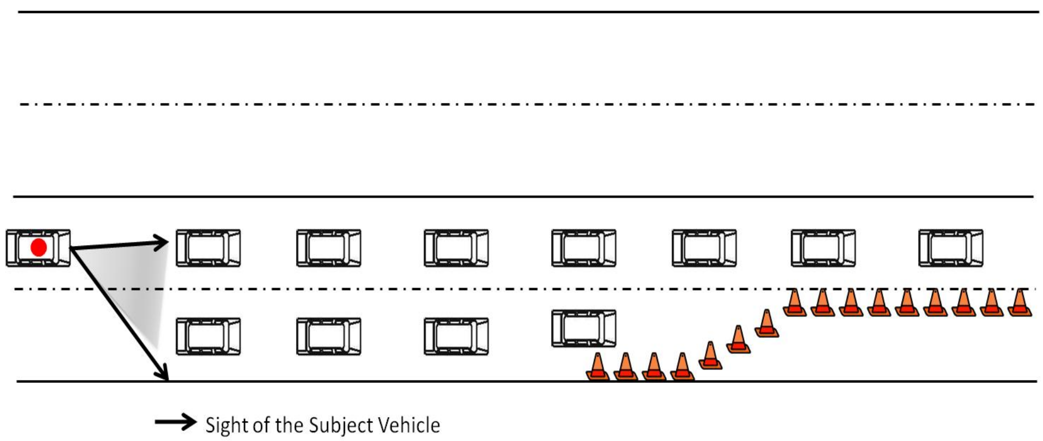


Figure 32 Sight of the Subject Vehicle in Work Zone Layout 1

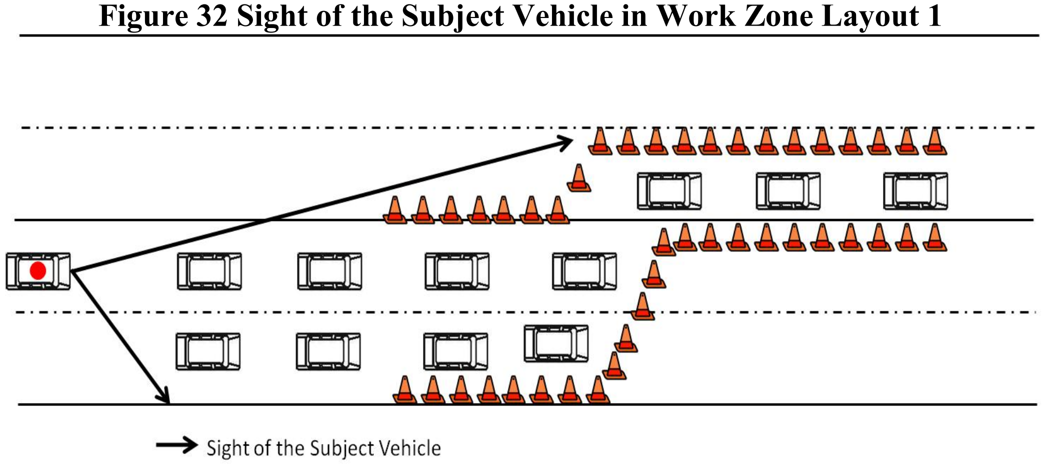


Figure 33 Sight of the Subject Vehicle in Work Zone Layout 2

2. The speed differences between two adjacent lanes at the merge point are different

Under Work Zone Layout 1, the speed of the traffic on the left lane could be higher than that of the traffic on the right lane because the right-lane vehicles have to yield to the vehicles on the left-lane in order to merge to the left lane and get through the work zone. This kind of maneuver can increase the safety risks and the VII based warning system can provide the headway and prevailing speed warning to reduce this risk. However, under Work Zone Layout 2, there is not much difference between the speeds on both lanes because the traffic on both lanes has to slowdown and merge into the same lane on other side of the roadway. In this situation, the additional information provided by the VII system may not be much helpful for the drivers merging and getting through the work zone safely. Therefore, no significant safety improvements are observed in the study scenario.

5.3.3 Analysis of Survey Results

A survey was conducted by the subjects who went through the driving simulator test. In the survey, the test subjects are required to evaluate the effectiveness of different work zone control measures, which are listed in Table 9 and give scores that are rated from 1 to 5 (1 means extremely helpful while 5 means not helpful at all).

Table 9 Work Zone Control Measures and Corresponding Codes

Code	Measure	Message	Category
1	Static Signs	Work Zone Ahead	Traditional
2	Dynamic Signs	Flashing Arrow	Traditional
3	Police Enforcement	Police Car with Flashing Light	Traditional
4	In-Vehicle Driver Warning	Work Zone Ahead	VII
5	In-Vehicle Driver Warning	Speed Limit	VII
6	In-Vehicle Driver Warning	Keep Safe Headway	VII
7	In-Vehicle Driver Warning	Prevailing Speed	VII

The survey result is analyzed by Microsoft Excel and SPSS software package. The mean scores are presented in Figure 34.

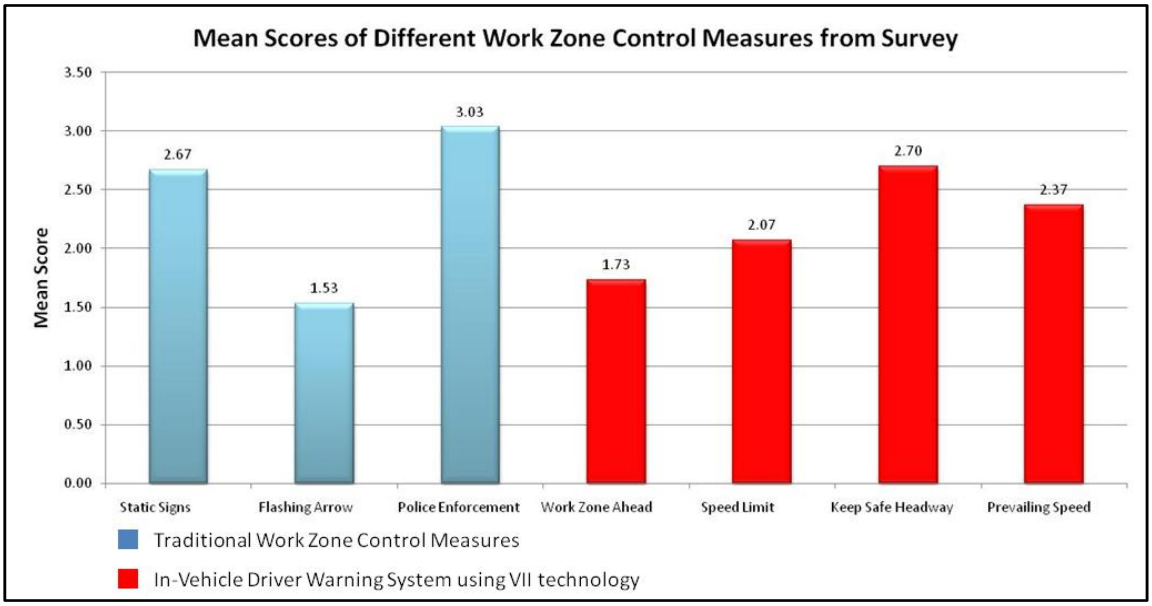


Figure 34 Average Score of Work Zone Control Measures

Tukey's Test *(31)* is conducted to find if there are significant differences among the scores of different work zone control measures. The results are shown in Table 10.

Table 10 Homogeneous Group Test Results for Work Zone Control Measures

Score

	Type	N	Subset		
			1	2	3
Tukey B[a,b]	2.00	30	1.53		
	4.00	30	1.73		
	5.00	30	2.07	2.07	
	7.00	30	2.37	2.37	2.37
	1.00	30		2.67	2.67
	6.00	30		2.70	2.70
	3.00	30			3.03

Means for groups in homogeneous subsets are displayed.
Based on Type III Sum of Squares
The error term is Mean Square(Error) = 1.626.

a. Uses Harmonic Mean Sample Size = 30.000.

b. Alpha = .05.

Tukey's Test categorizes the work zone control measures into several homogeneous groups based on the score they got (see Table 10). From the results presented in Figure 34 and Table 10, it is shown that Work Zone Control Measure 2 (Flashing Arrow) and 4 (Work Zone Ahead Voice Warning) are the most preferred work zone control measures while 3 (Police Enforcement) is the least preferred work zone control measure.

CHAPTER 5: SUMMARY, CONCLUSIONS AND RECOMMENDATIONS

This research is to investigate the application of the VII technology for preventing three types of highway collisions, i.e. Run of Road (ROR), lane change and work zone related collisions using various driving conditions. For this purpose, three VII-based driver warning systems (RHDWS, HLCWS and WZDWS) were designed and tested in a designed testing scenario by driving simulator experiments. The results of simulator experiments show that:

1. By using the RHDWS, 1) the number of critical events and ROR events can be significantly reduced, 2) the maximum deceleration of the subject vehicle can be significantly decreased, and 3) the percentage of drivers who conform to the posted speed limit can be significantly increased. These results indicate that the proposed warning system can effectively reduce the ROR crashes in a rural highway environment.
2. By using the designed HLCWS, the numbers of collisions and critical events during lane changes can be significantly reduced.
3. For the designed WZDWS, when the sight distance is limited at the work zone and/or the speed difference between lanes at the merge point are high (such as in Work Zone Layout 1), the designed VII based WZDWS can significantly reduce the work zone collision risk compared to the prevailing work zone safety control measures, including static warning signs, flashing arrow signs and police enforcement. When the sight distance is not limited at the work zone and the speed difference between lanes are not high, no significant improvement is observed for all of the five MOEs between the comparison and study scenarios. These findings indicate that VII technology has the potential to reduce the safety risks at work zones under situations where the drivers cannot be well informed about the coming work zone due to the limited sight distance of the work zone and/or the speed difference between lanes at the merge point ishigh. When a work zone can be easily identified in advance, the deployment of VII technology is less likely to bring additional safety benefits. Thus, engineering judgment is needed in the decision making for the implementation of the proposed VII based work zone collision prevention system.

After the driving simulator experiments, survey was conducted by the participants to solicit their opinions on the proposed VII technology based driver warning systems. The survey results show that most of the participants thought that the proposed driver warning systems were helpful to them for avoiding ROR, lane change and work zone related collisions and was easy for them to use. All these findings indicate that VII technologies can be successfully applied for preventing ROR, lane change and work zone related collisions and have great potential for improving the safety of the transportation system.

In addition, this research effort not only demonstrated that a driving simulator experiment is a cost-effective approach for analyzing the safety impacts of various traffic control measures, but also introduced a comprehensive set of surrogate MOEs specifically designed according to the data collection capabilities of the driving simulator. The frame work used in this research can be applied to other safety studies with different test scenarios.

For future study, a benefit and cost analysis should be conducted to provide quantified safety benefits and costs of applying VII technology to help decision making. More factors, including the time of day, weather conditions and different traffic congestion levels, should also be taken into account. Meanwhile, the rapid development of VII technology may introduce some more aggressive safety control strategies, such as an automatic brake system and an inter-vehicle speed monitoring system. These new strategies will be great research topics that can be further investigated using the frame work developed by this study.

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